MORPHOLOGY AND PHYSICS OF SHORT-PERIOD MAGNETIC PULSATIONS

(A Review)

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Abstract. This review is devoted to the main problems of experimental and theoretical investigations of geoelectromagnetic waves in the frequency range from 0.1 to 5 Hz. These waves constitute the short-period subclass of so-called geomagnetic pulsations. The short-period pulsations are represented by Pc1, Pc2, Pi1, Ipdp types and some subclassifications. The understanding of the pulsation mechanisms provides an insight into the structure and dynamics of the Earth's magnetosphere. We focus our attention on Pc1 'pearl' pulsations and on the classical (evening) Ipdp, for which basic physical concepts have been established. Other types and varieties are outlined also, but in less detail. In these cases, the physical mechanism is not always clear (as, for example, in the case of morning Ipdp), and/or the morphology is still to be determined carefully (Pc2 and discrete signals in polar cusps as typical examples).

Short-period pulsations are a spontaneous, sporadic phenomenon which undergo a certain evolution in the course of a magnetic storm. We consider the storm-time variation as a natural 'background', and we use this background to collect the information about the pulsations in an orderly manner. At the same time, together with the transient storm-time variation of pulsation activity, quasi-periodic variations take place, which are connected with the Earth's and Sun's rotation, Earth's orbital motion and solar cycle activity. The study of these regular variations allows us to have a new approach to the mechanisms of excitation and propagation of short-period geomagnetic pulsations.

Table of Contents

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1. Introduction

1.1. Short-period and long-period pulsations

Geoelectromagnetic waves in the period range between 0.2 s and 600 s are called geomagnetic pulsations (Jacobs, 1970; Nishida, 1978; Guglielmi and Pokhotelov, 1996). The term *short-period* is used here for the pulsations with periods of 0.2–10 s. They are represented by the Pc1, Pc2, Pi1, Ipdp types and many other variations (see Fukunishi et al., 1981; and Samson, 1991, for a more detailed classification and nomenclature). These pulsations are the subject of this review.

Short-period pulsations differ from *long-period pulsations* by a number of specific properties. Firstly, we must recognize that short-period pulsations are travelling waves, in contrast to long-period pulsations, which are often standing waves. Secondly, short-period pulsations display a spectacular frequency and amplitude modulation. Thirdly, these pulsations are a spontaneous, sporadic phenomenon, in contrast, for example, to Pc3, which are more persistent pulsations.

The amplitude modulation of Pc1 pulsations was pointed out in the first publications (Harang, 1936; Sucksdorff, 1936). This is well represented by the term 'pearl necklace', which was introduced by Sucksdorff (1936) as a reference to a quasi-periodic sequence of wave packets. However, more striking is the frequency modulation of pulsations. The search for mechanisms of frequency-amplitude modulation is a vital issue in the physics of short-period pulsations.

In this review, the main problems of both experimental and theoretical investigations of short-period pulsations are summarized. As the theoretical and experimental aspects cannot be separated, we do not make any sharp distinction between the morphology and the physics of pulsations.

The great number of papers dealing with short-period pulsations is indicative of a lively interest in a search for the interpretations of these pulsations. This is quite expected since the understanding of pulsation mechanisms provides an insight into the general structure and dynamics of the Earth's magnetosphere. Meanwhile, the modern problems of short-period pulsations have not been adequately reviewed. There has been notable progress after the old reviews by Campbell (1967), Troitskaya (1967), Troitskaya and Guglielmi (1967), Saito (1969), Orr (1973), and Guglielmi (1974). In the modern reviews by Samson (1991) and Guglielmi and Pokhotelov (1994), short-period pulsations are not completely described. This is especially true in the field of the morphology of these pulsations. We give a survey of the papers which contain valuable information about short-period pulsations, and which illustrate the crucial problems to be solved in the future. We discuss some of these problems in order to gain a better insight into the pulsation mechanisms.

1.2. Some historical notes

The history of geomagnetic pulsations has its roots in the 18th century. The first observations of long-period pulsations were reported as early as in 1741 by A. Celsius, who compared the compass measurements in Uppsala with pulsations of aurora. J. Nervander, a Finnish scientist, observed magnetic pulsations with a period of about 30 s by means of his declination variometer in Helsinki in the 1840s. According to B. Stewart, an English geophysicist, pulsations have been registered also at Kew Observatory near London in the course of a great magnetic storm in 1859. At the turn of the century, long-period pulsations had become the subject of systematic study.

The credit for the discovery of short-period pulsations is shared by two men: E. Sucksdorff from the Geophysical Observatory at Sodankylä, Finland, and L. Harang from the Auroral Observatory at Tromsø, Norway. Sixty years ago these scientists published their results containing the description of observations of magnetic pulsations, which are now called pearl pulsations or Pc1 (Figure 1). (For an extended description, see the historical essay by Mursula et al., 1994a). This review is dedicated to the sixtieth anniversary of this notable experimental discovery. Short-period pulsations still attract research interest as they provide information on the remote regions of the Earth's space environment, and the means for experimental study of different manifestations of the self-consistent interaction between waves and particles, and also because of their complex and puzzling behavior.

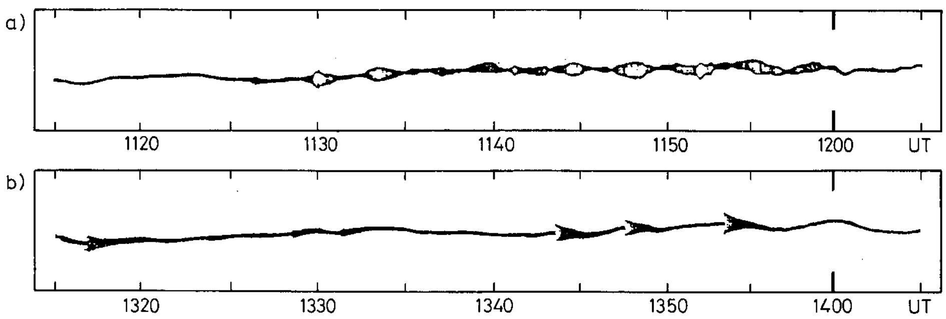

Figure 1. (a) A typical example of a chain of ‘pearl necklace’ registered by the Sodankylä quick-run magnetometer system, in operation already in 1930s. (b) The nonmicropulsational background mainly consists of the clearly distinguishable arrow-head or wedge-shaped formed signals caused by thunder (after Mursula et al., 1991).

1.3. Physics and Morphology

Many investigators have summarized the morphological properties of short-period pulsations. Figure 2 illustrates some major characteristics of the dynamic spectra of pulsations. It is known, e.g., how these regimes vary with the level of geomagnetic activity, with the phase of solar cycle, etc. On the other hand, the physical mechanisms of generation and propagation of pulsations are known only in specific cases. There is an overall need to translate the morphological properties of pulsations into the language of physics.

Because the basic equations describing geoelectromagnetic waves are known, one would think that an ultimate aim of such a translation is the mathematical evaluation of a wave phenomenon in the frame of some realistic model. But this aim cannot be reached in the most interesting cases due to the complexity of basic equations, and also due to the uncertainties in initial, boundary, and other supplementary conditions. Traditionally, we study strongly idealized models in the frame of one or another qualitative scenario describing the physical processes.

In some cases we have not even a scenario in analyzing the morphological properties. But even so, the general theory of oscillations and waves provides a basis for the creation of concepts and fundamental guidelines. For such a program the first problem is the search of the governing parameters of the oscillating system, and the second one is the determination of the critical values of these parameters. We attempt to solve both of these problems by a careful analysis of the changes in pulsation regime in the course of transient and quasi-periodic variations of the geomagnetic and solar activity.

1.4. Pulsations Occurring during Magnetic Storms

Short-period pulsations undergo a certain evolution during the course of a magnetic storm. We consider the storm-time variation as a natural ‘background’, and we use

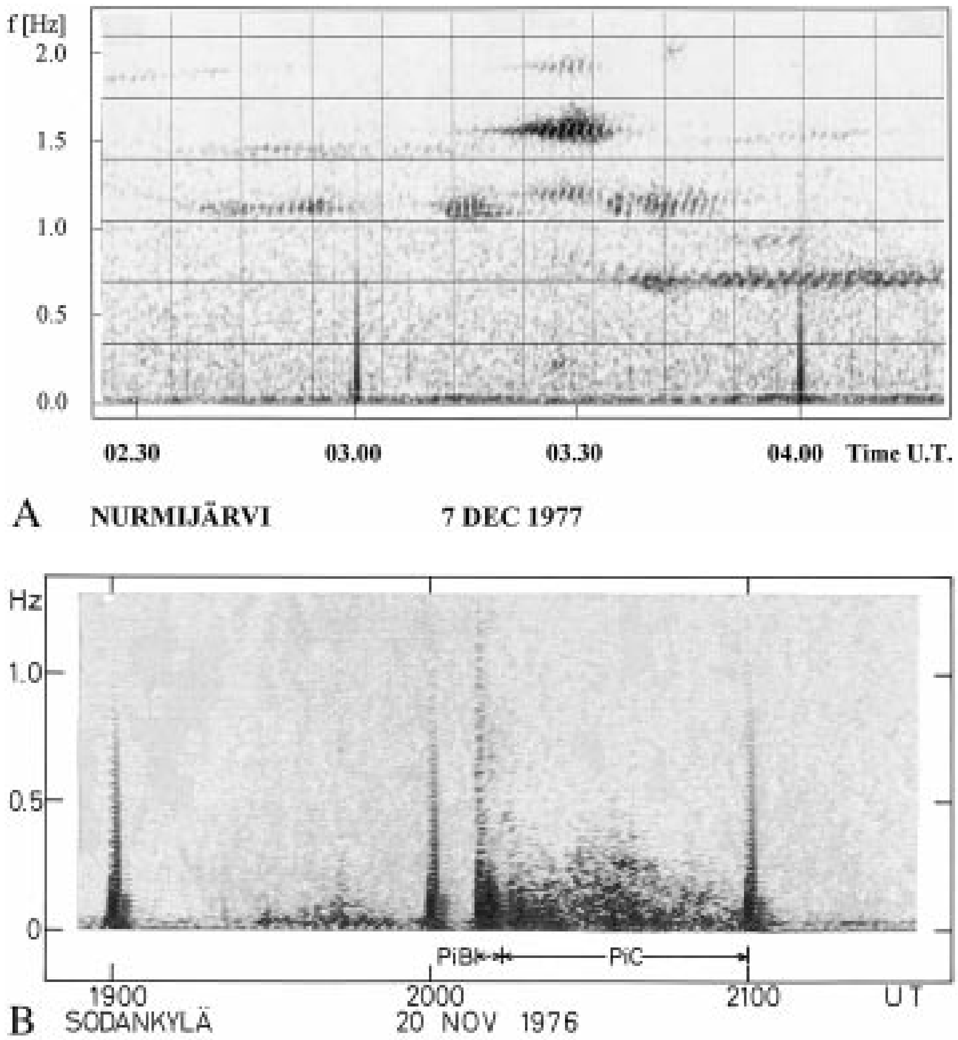

Figure 2. (a) Pearl or structured Pc1 pulsations recorded at Nurmijarvi on December 7, 1977. (b) PiB and PiC magnetic pulsations recorded in Sodankylä on November 20, 1976. (c) IPDP type plasma wave events observed in Sodankylä on July 8, 1993.

this background to present the information about short-period pulsations in an orderly manner.

Figure 3 gives a general view of the evolution of the pulsation regime during a magnetic storm. The upper panels represent the Dst storm-time variations. The sketchs of pulsation dynamical spectra are given below. We can see that during the high Sunspot years (Figure 3(a)) there are mainly PiB+PiC pulsations and short Pc1 events appear some days after the Dst minimum; during the low sunspot years (Figure 3(b)) there are PiB+PiC events too, but Pc1 events are longer and

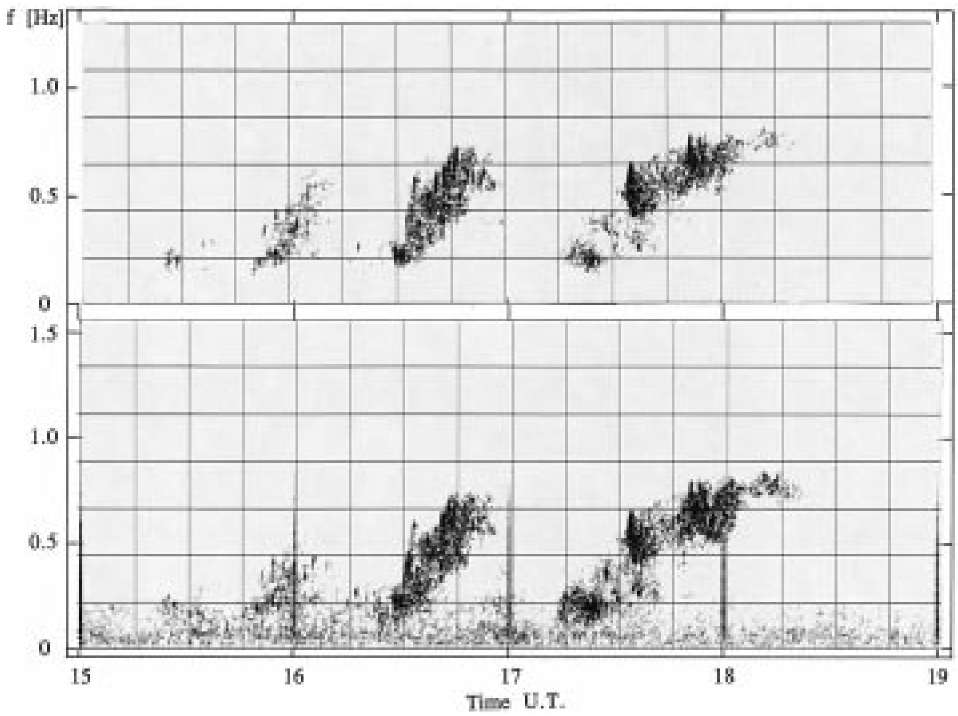

Figure 2. Continued.

they may appear shortly after the Dst minimum. At the time of the SSC there are usually Pi1–2 or PiB+PiC pulsations. Sometimes, when Pc1 pulsations occur simultaneously with the SSC the carrier frequency jumps to a higher level. During the main phase of storm the Ipdp events appear as a rule. Pc1 events occur mainly during the recovery phase of the storm.

We reserve a more detailed analysis for later sections of the review. Here, we point out only that the morphological investigations along these lines help us to establish the governing parameters which determine the oscillatory regime of the magnetosphere.

The main body of this review is contained in Sections 2–5. The transient storm-time evolution of the pulsation regime is considered in Sections 2–4. The quasi-stationary regular variations of the pulsation activity are described in Section 5. Geophysical and general physical applications are reviewed briefly in Section 6.

To facilitate the reading of the following chapters some abbreviations are listed here: Pc = continuous pulsations; Pi = irregular pulsations; Ipdp = interval of pulsations of diminishing periods; SI = sudden impulse; SSC, or SC = storm sudden commencement; Dst = storm-time disturbance. Designations Pc1, Pc2, Pi1, and Pi2 correspond to the pulsations with periods 0.2–5 s, 5–10 s, 1–45 s, and

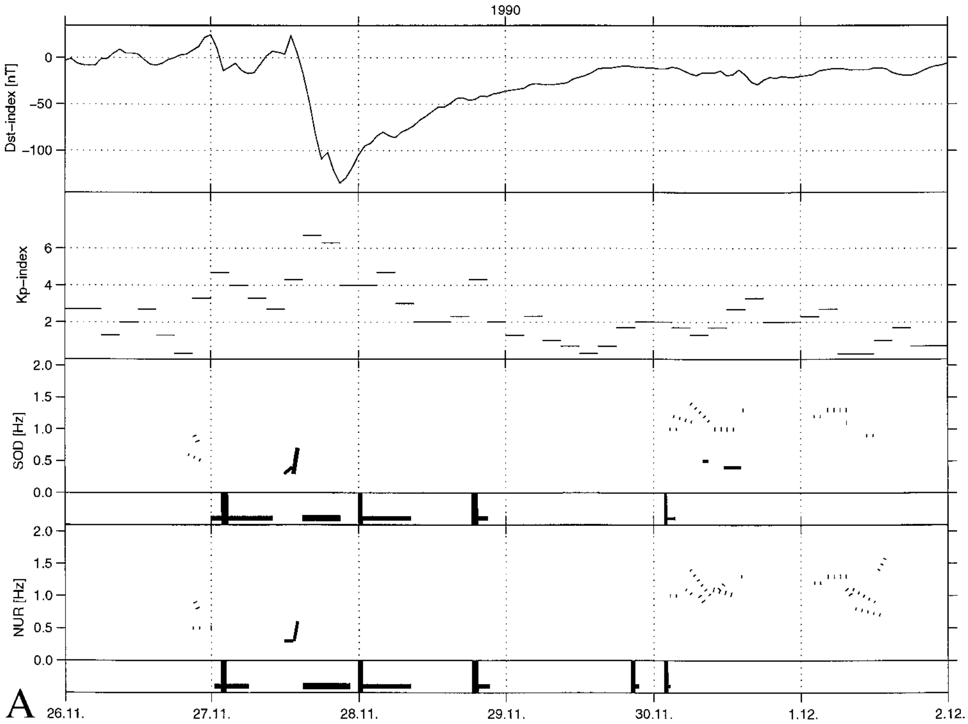

Figure 3. (a) Appearance of short-period magnetic pulsations in Sodankylä and Nurmijarvi during a magnetic storm in November 1990 (solar maximum year). Magnetic activity is shown by the Dst and Kp indices. (b) Same as in (a) but for the magnetic storm in October 1986 (minimum year).

Table I
Locations of Finnish riometer and pulsation magnetometer stations

	Geographic coordinates		L-value	Riometer	Pulsation magnetometer
	Latitude	Longitude			
Kevo	69.8	27.0	6.0	x	x
Ivalo	68.6	27.5	5.5	x	
Sodankylä	67.4	26.6	5.1	x	x
Rovaniemi	66.6	25.8	4.8	x	
Oulu	65.1	25.5	4.3	x	x
Jyväskylä	64.2	25.7	3.7	x	x
Nurmijärvi	60.5	24.7	3.3	x	x

45–150 s, respectively. Pulsation train Pi1+Pi2 is designated by PiB. Continuous irregular pulsations are called by PiC.

In the text we frequently use data from the Finnish chain of pulsation magnetometer and riometer stations. Table I provides information about the location of these stations. Due to the very nature of this review much attention is devoted to

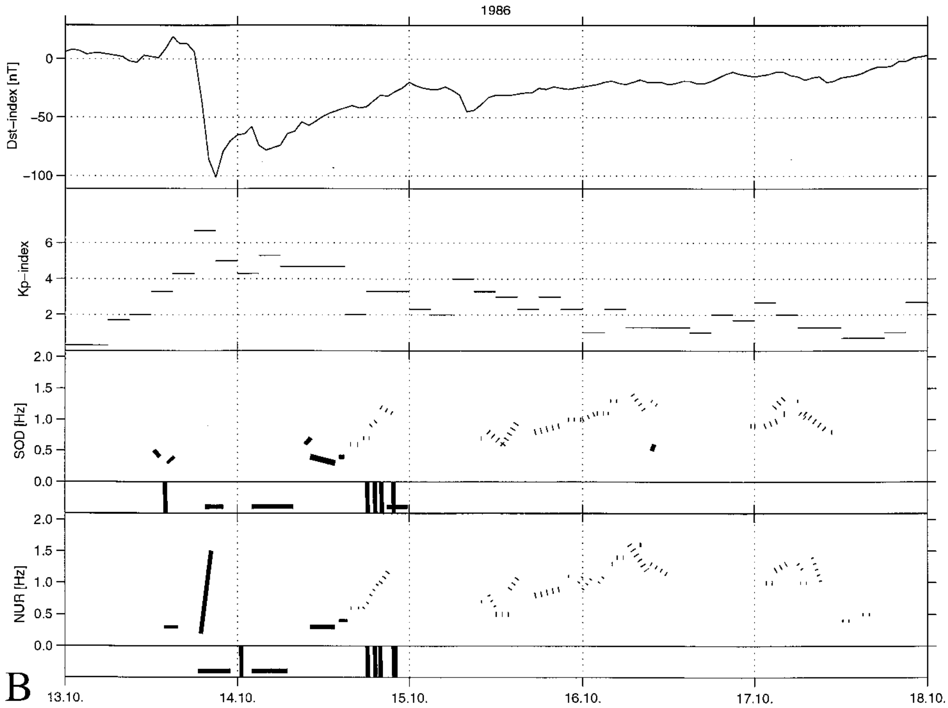

Figure 3. Continued.

the information obtained by ground-based recordings but references are made also to the satellite measurements which have become an essential part of the research.

2. Storm Sudden Commencement

2.1. Pulsations prior to SSC

In Section 2 we explore short-period magnetic pulsations before and after the interplanetary shock impact on the magnetosphere. Such an impact leads to a compression of the geomagnetic field, resulting in the so-called magnetic sudden impulse (SI). Often a geomagnetic storm follows (Akasofu and Chapman, 1972). In such a case, SI is called 'Storm Sudden Commencement', SSC or SC for brevity.

Heacock and Hessler (1965), Kokubun and Oguti (1968), Olson and Lee (1983), Kangas et al. (1986) have discovered that Pc1 pulsations are excited after sudden compression of the magnetosphere by a reasonably strong interplanetary shock (Figure 4(a)). Of course, Pc1 can also be excited spontaneously irrespective of interplanetary shocks. If the magnetosphere has been impacted by a shock front during such an event, there is a widening or a stepwise increase of the frequency of pulsations (Figure 4(b)).

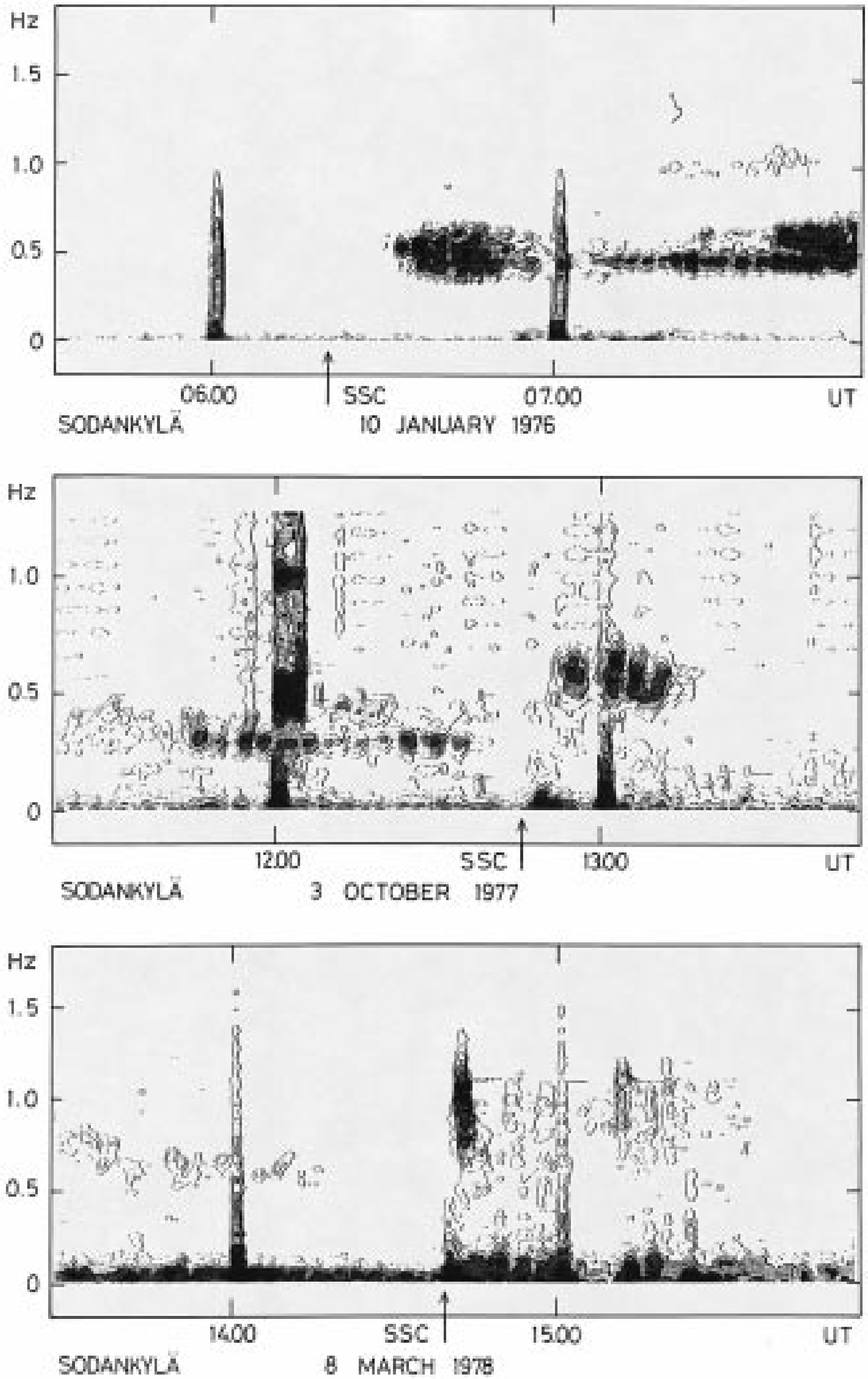

Figure 4. Types of ULF emission associated with SI's. (a) Pc1 pulsations induced by an SI. (b) Effects of an SI on ongoing Pc1 activity. (c) Bursts of ULF noise (after Kangas et al., 1986).

It is possible to develop a view on the Pc1 generation after SI which will be described in the subsections to follow. In this subsection we look at a more difficult problem of the influence of interplanetary shocks on pulsations before the SSC.

In a study of the amplitude dependence of Pc1-SC relations, based on the data in Kangas et al. (1986) we revealed a rather strange phenomenon. It was a great surprise, that most events prior to the contact of the interplanetary shock with the magnetosphere occur at the small amplitudes of SI ($A \sim$ 6–20 nT). One would think that the influence of the interplanetary shock on the Pc1 activity before the collision of the shock front with the magnetosphere does not exist at all. However, according to observations the probabilities of Pc1 occurrence before SI are equal to $P(A \leq 20\ \mathrm{nT}) = 0.32$ and $P(A > 20\ \mathrm{nT}) = 0.06$ (the populations include 47 and 50 events, respectively). The difference obtained is reliable at the 99% confidence level. This indicates that a sufficiently strong interplanetary shock suppresses the Pc1 activity prior to the contact with the magnetosphere.

Additional data for short-period pulsations before SI can be found in the literature. According to Troitskaya (1964), L. Tepley observed and discussed a Pc1 event before the storm of 30 September, 1961. This event coincided with solar cosmic-ray bursts in the stratosphere. Troitskaya (1964) also discussed many other cases of pulsations prior to SC which occurred simultaneously with an increase of proton flux in the energy range of 3–30 MeV. Recently Parkhomov (1992) reported an observation of broadband Pi1 pulsations simultaneously with gamma-emission from a solar flare.

Hence, there are some reasons to think that pulsations are modulated soon after a solar flare and well before the collision of the interplanetary shock wave with the Earth's magnetosphere. However, there is no theory that adequately explains these observations. We do not understand the physical mechanisms of generation and suppression of the magnetospheric oscillations prior to the direct influence of the shock front on the magnetosphere. This is an open fundamental problem, and for the time being, we can only enumerate the physical factors which are likely to be crucial in this context.

Solar γ-rays and cosmic rays have already been mentioned above. X-rays and ultraviolet radiation from the Sun should also be added. All these factors are active immediately after the solar flare, i.e., several tens of hours prior to SI, and they have nothing to do with the interplanetary shock front as such. The influence of the interplanetary shock starts only a few hours before the SI. The idea is as follows.

Kennel et al. (1982) discovered that the plasma phenomena in the upstream region of the Earth's bow shock (e.g., Paschmann et al., 1980, 1981; Russell and Hoppe, 1983; Anagnostopoulos et al., 1988) occur also in front of interplanetary blast shocks generated by solar flares. The geometry of a typical interplanetary shock front in the vicinity of the Earth's orbit (Taylor, 1969; Hundhausen, 1972) predicts that the leading edge of the foreshock comes into contact with the magnetosphere 5–10 hours prior to the SI. During these hours the periphery of the magnetosphere and the high-latitude ionosphere are exposed to the electromagnetic turbulence upstream and the interplanetary shock-reflected electrons and ions. Hence, the search for preceding the events SC may be based on the concept of specific structure of the interplanetary plasma ahead the shock front. One would expect that a change in intensity of geomagnetic and ionospheric phenomena starts a few hours prior to SC.

2.2. SC-INDUCED PC1 PULSATIONS

Figure 4(a) depicts the dynamical spectrum of Pc1 magnetic pulsations recorded at Sodankylä, Finland, 10 January, 1976. The vertical arrow indicates the SI occurred at 06:20 UT. A train of oscillations, which is limited to a frequency band between 0.4 Hz and 0.7 Hz, begins 10 min after the SC. Sometimes the SI-induced pulsations have the form of broad-band short-lived bursts (Figure 4(c)) .

These pulsations are obviously caused by the interplanetary shock wave and they differ from those discussed in Subsection 2.1. This is particularly notable when both types of pulsations are associated with the same SC. Figure 5 illustrates the situation. One notes that Pc1 pulsations are in progress with the frequency of about 0.3 Hz at Kevo and Nurmijarvi before the SI. At the time of SI an enhancement of the intensity occurs and a small increase in frequency is also seen. About 4 min after the SI, a burst-like emission was recorded at both stations extending from about 0.6 to about 1.2 Hz. This is followed by Pc1 pulsations at about 1.2 Hz at Kevo, but these pulsations are missing in the recordings of the low-latitude station Nurmijarvi. The causal relation of Pc1 with the interplanetary shock is evident for the pulsations at 1.2 Hz, whereas it is possible that the appearance of pulsations at 0.3 Hz before the SI has nothing to do with the interplanetary shock (see, however, Subsection 2.1).

The morphology of SC-induced short-period pulsations has been studied in detail by Troitskaya (1961), Tepley and Wentworth (1962), Heacock and Hessler (1965), Saito and Matsushita (1967), Kokubun and Oguti (1968), Olson and Lee (1983), Kangas et al. (1986), and Anderson and Hamilton (1993). It has been found that an enhancement of Pc1 wave activity on the ground after SI occurs in $\frac{2}{3}$ of cases at least (Kangas et al., 1986). It is interesting to compare this result with satellite data. According to Anderson and Hamilton (1993), only 47% of SC events were associated with the local onset of Pc1. Appearance of pulsations is most probable in the noon sector of the magnetosphere. There is a delay of a few minutes between the SC onset and the start of pulsations. The preceding magnetic activity influences the probability of the Pc1 appearance: Kp for the 3-hr interval preceding the SC is lower for the cases with Pc1 than Kp for the cases where no Pc1 was noted after SC. By and large, the cases when no pulsations after SC can be identified are more numerous during high solar activity. However, the bursts of pulsations (Figure 4(c)) are most frequently observed in the years of high solar activity (Kangas et al., 1986).

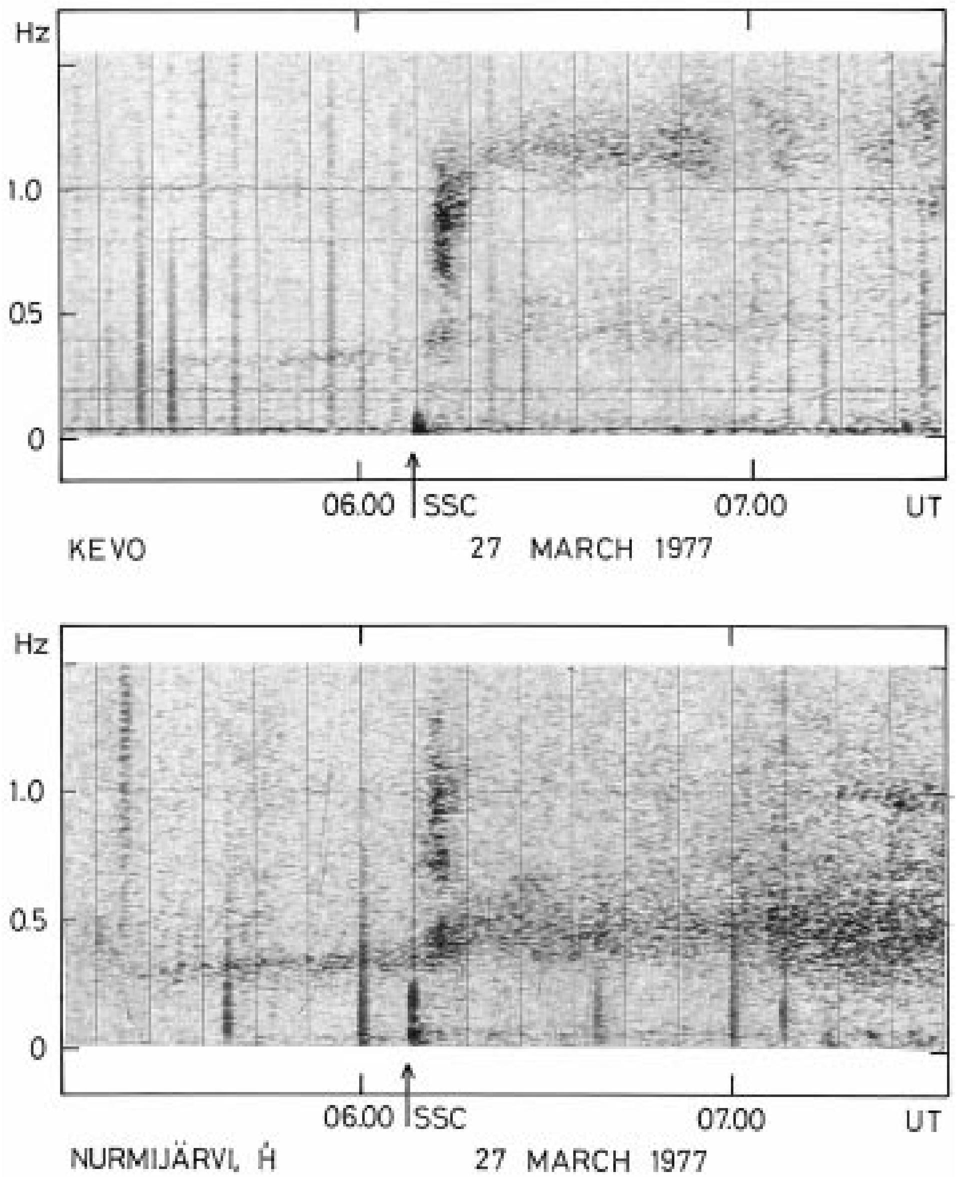

Figure 5. ULF emissions observed at Kevo and Nurmijarvi on March 27, 1977 (after Kangas et al., 1986).

Our main interest here is to investigate the most important physical parameters necessary for the excitation of Pc1 pulsations by SC and to estimate their threshold values. One would expect that the intensity of the interplanetary shock is one important governing parameter. We can use the amplitude A of SI as a measure of this parameter. Additional parameters must be called on to describe the state

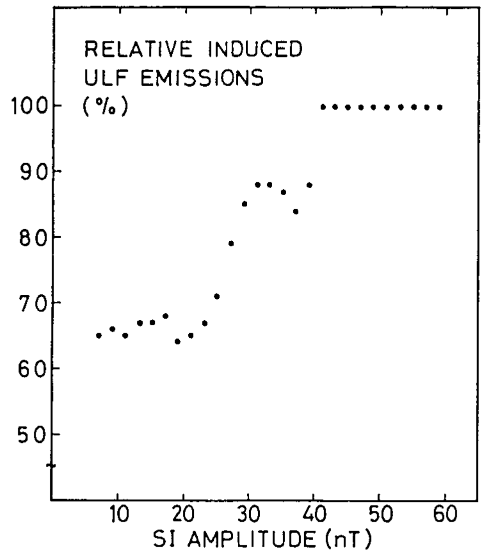

Figure 6. Relative induced Pc1 waves in per cents when the Sl amplitude is more than a given value (after Kangas et al., 1986).

of magnetosphere. As a rough overall parameter we can use the Kp index for the interval preceding the SI.

Figure 6 shows the induced pulsation activity when the SC amplitude is above a given value (Kangas et al., 1986). The first amplitude threshold of approximately 10 nT is necessary for the stimulation of pulsations. As A rises above 25 nT the number of observed Pc1 rises dramatically. Above 40 nT all SIs are associated with Pc1. It may appear that there are three critical values of the governing parameter, namely, 10, 25, and 40 nT. Let us show that most likely we are dealing with two thresholds and not three.

We can state quite convincingly that the excitation of Pc1 is not simply a passive reaction of the geomagnetic field on an impact perturbation. Indeed, the occurrence of Pc1 after SI is random. One further reason is as follows: the lifetime of a wave packet with the carrier frequency of 1 Hz in the magnetosphere is of no more than several minutes, whereas the Pc1 series induced by SI is much longer. There is an impression that we are dealing with a compound process rather than with the direct shock excitation of an oscillatory system.

We propose that a two-step mechanism is brought into action due to quick compression of the geomagnetic field. In the initial stage the energy of the interplanetary shock is partially converted into a form of free energy stored in the magnetosphere (Olson and Lee, 1983). In the second step the ion-cyclotron waves are excited as a result of an unstable ion distribution, resulting in the appearance of Pc1 waves on ground. However the second step occurs if the waves are guided to the ground along the geomagnetic field lines, and the free energy of ions within a particular waveguide is above the threshold. The former condition is fulfilled, e.g., at the plasmapause, the position of which depends on the geomagnetic activity and varies from $L \approx 3$ to $L \approx 7$ approximately, where L is the McIlwain parameter (e.g., Roederer, 1970). The latter condition requires that the amplitude A of SC exceeds a critical value $A_c(L)$ which depends on the position of the waveguide. Here $A_c(L)$ is assumed to be decreasing function, which is in general agreement with the results of computer simulation (Olson and Lee, 1983; Anderson and Hamilton, 1993). Thus there exists an inverse function $L_c(A)$ such that $\mathrm{d}L_c/\mathrm{d}A < 0$.

We introduce the distribution function of the waveguides $g(x)$, where $x = L/L_m$. L_m is the geocentric distance to the boundary of magnetosphere after compression. Then the probability of Pc1 occurrence after SC is equal to

$$P(A) = \int_{x_c(A)}^{1} g(x)\ \mathrm{d}x\ . \tag{1}$$

Hence the occurrence of Pc1 after SC is a random event with a probability depending on the intensity of interplanetary shock as well as on the density of the probability distribution of the magnetospheric waveguides.

From Equation (1) follows

$$\frac{\mathrm{d}P}{\mathrm{d}A} = -g[x_c(A)]\frac{\mathrm{d}x_c}{\mathrm{d}A}\ . \tag{2}$$

In principle, given the function $x_c(A)$, Equation (2) makes it possible to determine distribution $g(x)$ from an empirical function $P(A)$. This latter has to be a non-decreasing function since $\mathrm{d}x_c/\mathrm{d}A < 0$ and $g(x) \geq 0$, *a priori*.

We have made a statistical study of the $A - P$ relation with data from the Finnish magnetometer network presented by Kangas et al. (1986). Four years of data and about one hundred series of Pc1 associated with SC were analyzed. The events are very unevenly distributed with respect to the SC amplitude. There is an overall increasing trend of P with A (see Figure 7). The pulsations after SC are absent for the small amplitudes ($A < 10$ nT), and they are present always if the amplitude is big enough ($A > 40$ nT). However the empirical probability fluctuates a lot for intermediate amplitudes.

A continuous piecewise line $P(A)$ has been drawn in Figure 7 to give a simple fit to experimental data. The derivative of this curve includes two broad maxima. According to Equation (2) the distribution function $g(L)$ of magnetospheric waveguides is represented qualitatively by the shape of this curve. The right side maximum corresponds to the permanent waveguides at the plasmapause, the left side maximum relates to sporadic waveguides outside the plasmasphere. Accordingly, the excitation of sporadic wave-guides occurs above the first threshold at 10 nT. When $A > 20$ nT, the excitation of the permanent waveguides takes place. The exact value of the second threshold depends on the state of the magnetosphere,

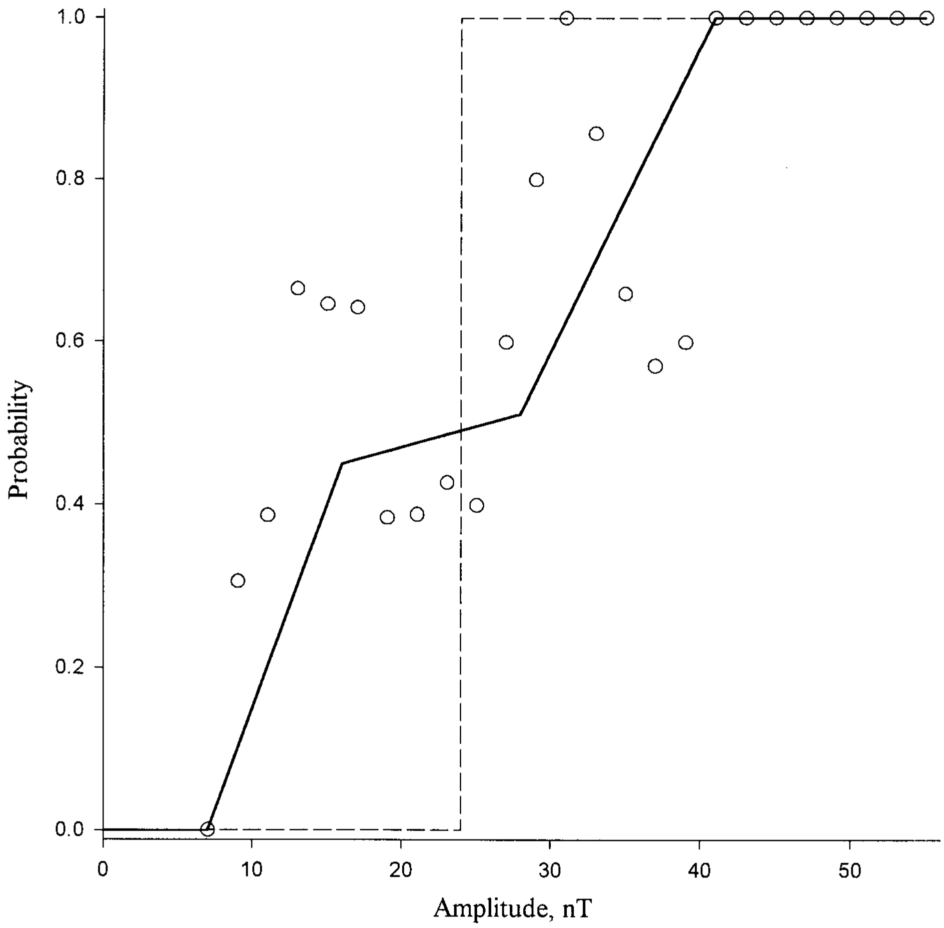

Figure 7. Probability P of Pc1 wave occurrence as a function of SI amplitude A. Circles represent experimental data. A rough approximation by the Heaviside step function is indicated by a dashed line. A more precise approximation is given by the piecewise curve.

or to be more specific, it depends on the position of the plasmapause, which in its turn depends on the preceding geomagnetic activity. This is the reason why Kp for the interval preceding the SC is lower for the cases with Pc1 than the Kp for the cases where no Pc1 was noted after SC.

2.3. Ion-cyclotron instability stimulated by magnetospheric compression

The idea of Pc1 as a manifestation of ion-cyclotron instability was suggested by Gintzburg (1961) and Cornwall (1965), and it was developed by many authors. The extensive literature on this subject is reviewed by Troitskaya and Guglielmi

(1967), Samson (1991), and Anderson (1996). We consider here the concept of ion-cyclotron instability, when applied to the SC-induced Pc1 pulsations.

Let us introduce the order parameter ε and the governing parameter Λ. The first one describes a state of an oscillatory subsystem of the magnetosphere. Setting ε equal to the square of the amplitude of Pc1 magnetic pulsations $\mathbf{b}$ averaged over some characteristic period of fluctuations ($\varepsilon = \overline{|\mathbf{b}|^2}$), we obtain the evolution equation

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = 2\Gamma\varepsilon \; , \tag{3}$$

where $\Gamma(\Lambda, \varepsilon)$ is the nonlinear increment. It is anticipated that before SC the state of magnetosphere is characterized by one or other ordering and symmetry, but the pulsations are absent ($\varepsilon = 0$); then, after SC a phase transition occurs, and a new state with Pc1 ($\varepsilon \neq 0$) appears. In this new state the ordering is higher but the symmetry is lower. The bifurcation and appearance of the new state are due to the change of the governing parameter Λ through a critical value Λ_c.

Equation (3) corresponds to this scenario if

$$\Gamma(\Lambda, \varepsilon) = \gamma(\Lambda) - \alpha\varepsilon \; , \tag{4}$$

where α is the (positive) coefficient of nonlinearity, and

$$\gamma(\Lambda) = \eta(\Lambda - \Lambda_c) \tag{5}$$

is the linear increment of instability near the threshold ($\Lambda \sim \Lambda_c$), and η is a parameter of the model yet to be determined. At $\Lambda < \Lambda_c$ in the steady state there are no pulsations ($\varepsilon = 0$). When crossing the threshold ($\Lambda > \Lambda_c$) the magnetosphere exhibits a phase transition of the second kind, and $\varepsilon = \gamma/\alpha$, or

$$b \propto (\Lambda - \Lambda_c)^{1/2} \; , \tag{6}$$

i.e., the pulsation amplitude is proportional to the square root of supercriticality.

In principle, the last relation offers an opportunity for testing of our concept by experiments, if we assume that $\Lambda \sim A$. This speculation is based on the empirical relations which were described in the previous subsection. Moreover, Olson and Lee (1983) and Anderson and Hamilton (1993) have estimated, on theoretical grounds, that the qualitative relation between A and Λ may be found through consideration of the changes of ion distribution in the magnetosphere due to compression of the geomagnetic field by interplanetary shock wave.

The resonance condition for the ion cyclotron instability is given by

$$\omega = kv_z + \Omega \; , \tag{7}$$

under which the exchange of energy between the ion-cyclotron waves and ions is most effective. Here k is the wave number, v_z is z-component of the ion velocity, Ω is the gyrofrequency of ions. The axes of local Cartesian coordinate system are fixed in such a way that the local geomagnetic field $\mathbf{B}$ is parallel to axis z. It is supposed that the wave has the form of exp$(ikz - i\omega t)$. Equation (7) means that the Doppler-shifted frequency $\omega' = \omega - kv_z$ in the moving reference system equals to the gyrofrequency: $\omega' = \Omega$. To the resonance condition (7) must be added the dispersion relation

$$k(\omega) = \frac{\omega}{c} n(\omega) \ , \tag{8}$$

where c is the velocity of light, and $n(\omega)$ is the refractive index for the ion-cyclotron waves. If the background plasma is cold, and it consists of electrons and ions of one kind, then

$$n(\omega) = \frac{c}{c_{\mathrm{A}}} \left(1 - \frac{\omega}{\Omega}\right)^{-1/2} \ , \tag{9}$$

where c_{A} is the Alfvén velocity.

It is evident that resonance takes place if the wave and the test resonant particle move in opposite directions ($kv_z < 0$). Taking this into account, we derive from Equations (7)–(9)

$$\left(\frac{\Omega}{\omega}\right) \left(1 - \frac{\omega}{\Omega}\right)^{-3/2} = \frac{w_{||}}{c_{\mathrm{A}}} \ , \tag{10}$$

which gives us the resonance frequency in the implicit form. Here we introduce the annotation $w_{||} = |v_z|$ for a 'representative' particle. If $w_{||} \gg c_{\mathrm{A}}$ then the approximate explicit expression

$$\omega \approx \left(\frac{c_{\mathrm{A}}}{w_{||}}\right) \Omega \tag{11}$$

follows from Equation (10).

It is now possible to assign the order parameter ε_ω with values which are defined by Equation (10). However, two uncertainties remain. First, what value should be taken as a 'representative' one for $w_{||}$; second, it is not evident at what point in the magnetosphere the values Ω and c_{A} should be taken.

The resolution of both issues may be found by calculation of the local coefficient of amplification $q = -\mathrm{Im}\, k$ in the frame of linear theory of ion-cyclotron waves by taking into account the energy exchange between the hot ions and the waves (e.g., Nishida, 1978; Samson, 1991; Guglielmi and Pokhotelov, 1996). As the distribution of energetic particles in the magnetosphere is anisotropic we shall take as a model the Maxwell distribution with different temperatures along ($T_{||}$) and across ($T_{\perp}$) the magnetic field. Then

$$q(\omega) = \frac{2\pi^{3/2} e^2 \Omega N'}{mc^2 k^2(\omega) w_{||}} \left[\frac{T_\perp}{T_{||}} \left(1 - \frac{\omega}{\Omega} \right) - 1 \right] \exp \left[- \left(\frac{\Omega - \omega}{w_{||} k(\omega)} \right)^2 \right] , \qquad (12)$$

where e and m are the ion charge and mass, respectively, N' is the concentration of energetic ions, $w_{||} = (2T_{||}/m)^{1/2}$. It is supposed that $N' \ll N$, where N is the concentration of the cold background ions. Amplification occurs when $T_\perp > T_{||}$, with $q(\omega) > 0$ at the frequencies

$$\omega < \left(1 - \frac{T_{||}}{T_\perp} \right) \Omega , \qquad (13)$$

as is clear from Equation (12).

Let us consider Equation (12) in the simple case when $c_A \ll w_{||}$. Then approximately

$$q(\omega) = 2\pi^{3/2} \frac{eJ\Delta}{cB} F[g(\omega)] , \qquad (14)$$

where $J = N' w_{||}$ is the flow of anisotropic ions along magnetic field lines, $\Delta = (T_\perp - T_{||})/T_{||}$ is the measure of temperature anisotropy, and

$$F(g) = g^2 \exp(-g^2) , \qquad g(\omega) = c_A \Omega / w_{||} \omega .$$

Differentiation of q with respect to frequency leads to the conclusion that the amplification is maximal at $g = 1$, this is equivalent to the resonance condition (11) with the proviso that the ‘characteristic’ velocity in Equation (11) equals the mean thermal velocity along the magnetic field.

Next, it is evident from Equation (14) that q peaks at the minimum value of B along the wave trajectory. In the dipole magnetic field this corresponds to the equatorial plane. Hence, if L is the McIllwain parameter of the wave trajectory (which coincides with a magnetic field line), then the parameter of ordering ε_ω, corresponds to the frequency which depends on L in the following manner:

$$\omega(L) = \text{const.} L^{-6} w_{||}^{-1}(L) N^{-1/2}(L) . \qquad (15)$$

The constant is approximately equal to 2×10^{14} in the CGS system.

We now proceed to study the governing parameter Λ in its relation with SC. Equation (14) suggests that the product of particle flow and anisotropy is a conventional form of the governing parameter:

$$\Lambda = J\Delta . \qquad (16)$$

In order to estimate the threshold Λ_c we start with the following expression:

$$\int q \, \mathrm{d}z - \{\text{losses}\} \ . \tag{17}$$

Here the first term is the wave amplification along a geomagnetic field line, and second one represents all kinds of wave dissipation. The rigorous calculation of the second term is quite complicated. To get a general idea, let us take into consideration that due to curvature of geomagnetic field lines, the propagation of wave along these lines is possible only in a longitudinal waveguide or duct, as it is called. Then the main mechanism of dissipation is the wave leakage into the ionosphere, and hence the second term is of the order of ln R^{-1}, where R is the coefficient of ionospheric reflection. Now, by using Equations (14)–(17) we obtain

$$\Lambda_c \propto \frac{1}{L^4} \ln\left(\frac{1}{R}\right) \ . \tag{18}$$

Finally, we can in principle calculate the linear increment

$$\gamma = \frac{1}{\tau}\left(\int q \, \mathrm{d}z - 2\ln\frac{1}{R}\right) \ , \tag{19}$$

and then estimate the coefficient η by combining Equations (5), (14), (16), and (19). Here we use the symbol τ for the Pc1 repetition period (see below in Section 3 for the details). The coefficient 2 in the second term in (19) appears due to the reflection of wave twice (from north and south hemispheres of the ionosphere).

We see from Equation (18) that the threshold Λ_c is a decreasing function of L, as it was suggested. However, we have been using the SC amplitude A and not Λ in the previous subsection. Are A and Λ related in some way? This can be demonstrated in the following.

The compression of the magnetosphere leads to an overall increase of the geomagnetic field by δB (which is proportional to A), and also to the displacement of charged particles across the magnetic shells by $\delta L/L \approx -\delta B/2B$ due to the electric field drift. As a result, the particles find themselves in an enhanced magnetic field: $B \rightarrow B + (\frac{5}{2})\delta B$ near the equatorial plane of the dipole field (Troitskaya and Guglielmi, 1967). This leads to an enhancement of the transverse temperature, since $T_\perp \propto B$ due to the conservation of the first adiabatic invariant. The longitudinal temperature is increased too but not so much. According to Cowley and Ashour-Abdalla (1975) $T_{||} \propto B^\nu$, where ν is $\frac{2}{3} - \frac{5}{6}$ (see also Southwood and Kivelson, 1975; and Olson and Lee, 1983). Therefore the anisotropy is enhanced after SC since $\nu < 1$. Let us suppose for simplicity that $\Delta = 0$ before SC; then after SC $\Delta = 2.5(1 - \nu)\delta B/B$. By using the second Chew–Goldberger–Low adiabatic invariant, it can be found that $N' \propto BT_{||}^{1/2} \propto B^1 + \nu/2$, and hence $J \propto B^{1+\nu}$, that is the flow is increased after SC. Taking into account all above relations and omitting the term $\sim (\delta B)^2$, we obtain $\Lambda \approx 2.5(1 - \nu)J\delta B/B$. We know that $A \propto \delta B$, and $\Lambda_c \propto L^{-4}$ (see Equation (18)). Therefore

$$A_c(L) = \frac{\text{const.}}{L^7 J(L)} \,. \tag{20}$$

Thus, the threshold A_c is a decreasing function of L as long as the flow J decreases with L more slowly than L^{-7}.

The decrease in threshold with L explains the experimental fact that the occurrence of Pc1 after SC increases with L (Anderson and Hamilton, 1993). The noon maximum of Pc1 occurrence may be explained by the specific axial asymmetry of geomagnetic field; the dependence of this occurrence on the Kp preceding the SC is interpreted by a dependence of the magnetospheric 'radius' on the solar wind force. The interpretation of these effects requires in general a computer simulation of the ion-cyclotron instability in the nondipolar magnetosphere (Olson and Lee, 1983; Anderson and Hamilton, 1993).

2.4. Sudden change in amplitude and carrier frequency

What do we know about the wave process if we observe a Pc1 with carrier frequency ω and amplitude b? Practically nothing. According to Equation (10) the frequency ω depends on three parameters Ω, c_{A}, and $w_{||}$ which are not known. With a knowledge of the carrier frequency alone, it is impossible to determine even a seat of the generation process. With the amplitude b the case is not improved. A completely different situation occurs in the case when a Pc1 series is disturbed by SC. Then we have two frequencies $\omega_{\mp}$ and two amplitudes $b_{\mp}$, where $-$ and $+$ correspond to the values before and after SC, respectively. In combination with the SC amplitude A, these values carry enough information to establish the wave process.

Let us return to Equation (6), and let us rewrite it in the forms $b_+^2 \propto \Lambda_- \Lambda_c$, $b_-^2 \propto \Lambda_- - \Lambda_c$. We subtract b^2 from b_+^2 to avoid the unknown parameter Λ_c: $b_+^2 - b_-^2 \propto \Lambda_+ - \Lambda_-$. The right side of this relation is proportional to A and we can write

$$b_+^2 - b_-^2 \propto A \,. \tag{21}$$

This is the relation which may be checked experimentally. This is a test for verification of our present view on the origin of Pc1 pulsations. We can not use A but a more representative characteristic of interplanetary shock, for example, the dynamical pressure of solar plasma ahead (p_-) and behind (p_+) the shock front. Then we obtain

$$b_+^2 - b_-^2 = \Phi(\mathrm{LT},\ \mathrm{Kp})(\sqrt{p_+} - \sqrt{p_-})$$

instead of Equation (21). The function Φ decreases with Kp increasing, and it has a maximum value at 12 hr LT.

The study of the change of the carrier frequency $\delta\omega = \omega_+ - \omega_-$, allows us to derive an additional useful relation (Troitskaya and Guglielmi, 1967; Guglielmi and Pokhotelov, 1996). To do this one needs a model of SC. We consider the unperturbed field B as a dipolar, and choose the simplest approximation of the disturbance δB due to SC. We assume that the disturbance has a potential and the most significant terms can be given by

$$\delta B_r = -\delta B(t)\left[1 - \left(\frac{R_{\rm E}}{r}\right)^3\right]\cos\vartheta\ ,$$

$$\delta B_\vartheta = \delta B(t)\left[1 + \frac{1}{2}\left(\frac{R_{\rm E}}{r}\right)^3\right]\sin\vartheta\ ,$$

where $R_{\rm E}$ is the Earth radius, r is the geocentric distance, ϑ is the polar angle measured from the dipole axis, and $\delta B(t)$ is the SC perturbation of magnetic field at the equatorial plane far from the Earth, $\delta B_- = 0$, $\delta B_+ = \delta B_{\rm max}$. If A equals the SC amplitude at the Earth's equator, then $\delta B_{\rm max} = (\frac{2}{3})A$. The induction electric field will cause the drift of resonant particles across the magnetic shells by $\delta L \approx -(A/3B)L$. The gyrofrequency of displaced particle will change by $\delta\Omega \approx 5eA/3mc$. Relative changes of Alfvén velocity and resonant velocity are equal to $\delta c_{\rm A}/c_{\rm A} \approx 2A/3B$ and $\delta w_{||}/w_{||} \approx 5A/2B$, respectively. Referring to Equation (11) it follows that $\delta\omega \approx (16A/9B)\omega$, or

$$\delta f\ ({\rm Hz}) \approx 0.027 XA\ ({\rm nT})\ . \qquad (22)$$

Here $X = \omega/\Omega$, where Ω is the gyrofrequency of protons in the region of Pc1 generation.

The value $\delta f = f_- - f_+$ is easily measured by analyzing the Pc1 sonogram. The value A is determined by standard magnetograms of equatorial observatories. Experimental data shows a rather good correlation between δf and A (Guglielmi and Pokhotelov, 1996). On the average $\delta f/A \approx 1.2 \times 10^{-2}$ Hz nT^{-1}. Comparing this with Equation (22) we find that the mean value $X \approx 0.44$ is not small. In these cases, Equations (11) and (22) may be used for a rough estimate only and more accurate coefficient of proportionality between δf and A should be calculated by the general formula (10).

Nishida (1978) has noted that the SC amplitude observed on the ground is decreased approximately by a factor of 2 due to influence of the ring current particles. Should this be the case then $X \sim 0.2$, i.e., the frequency of Pc1 is less than the gyrofrequency of He^+ ions in the region of generation.

2.5. Pulsations in the Initial Phase of Magnetic Storm

The initial phase of the geomagnetic storm is the interval between SC and the onset of a severe decrease in the H-component of the geomagnetic field which is characteristic of the main phase. The duration of initial phase varies considerably from storm to storm. It may be as short as 20 min, and as long as 5 hr. Pc1 pulsations last usually for all this time, if they were stimulated by SC. These Pc1 series are often accompanied by Pi1 bursts or Pi1 noise in the lower frequency band (see Figure 4).

Many scientists have presented evidence that other types of pulsations are exited also during the initial phase. The mechanisms of these pulsations attract particular interest because the changes in oscillatory regime of the magnetosphere reflect a complicated and poorly explored structure of the interplanetary plasma behind the shock front. However, the physical interpretation of observations is often difficult. We restrict the discussion to the cases of Pc2 and Ipdp.

The Pc2 pulsations that may appear on the day-side in the course of the initial phase might be simply due to the upstream magnetosonic waves. Upstream waves are typically observed on the ground as Pc3 pulsations with the carrier frequency

$$f = gB \; , \tag{23}$$

where B is the interplanetary magnetic field in front of the magnetosphere, and $g = 5.8 \pm 0.3$ mHz nT^{-1} (Guglielmi, 1974). In the initial phase of the magnetic storm the magnetosphere is surrounded by compressed solar wind. Compression of the magnetic field B behind the shock front leads to a rise in frequency. At $B > 17$ nT according to Equation (23) we have $f > 0.1$ Hz, which is in the range of Pc2 pulsations. An additional argument is as follows. According to Hundhausen (1972) a compressed solar wind contains a structural element (shell) which is enriched by He^{++} ions. When this element pass the magnetosphere, the transition to the Pc2 frequency range occurs at $B > 35$ nT, since the gyrofrequency of He^{++} ions is a half of that of protons.

However, we cannot exclude the possibility that Pc2 are generated in the magnetosphere or on the magnetopause. The current theory leaves room for the possibility of a self-excitation of geomagnetic pulsations inside the magnetosphere for a wide range of frequencies. This problem may be solved only by a crucial experiment. We shall return to this problem in the next section.

The appearance of Ipdp in the initial phase poses a much more difficult problem. As a rule, Ipdp's are observed in the evening hours after a substorm onset. Figure 8 is an example: the interval of pulsations begins immediately after SC at the mean frequency ~0.25 Hz and finished half an hour later (in the course of initial phase) with mean frequency ~0.7 Hz. We do not understand the mechanism of such abnormal behavior. Further morphological investigations are needed. Low-energy particle injections associated with SC (Arnoldy et al., 1982) may be the energy source of IPDP's observed in the initial phase of magnetic storm.

3. Main Phase of Magnetic Storm

The main phase is developed due to interaction of the magnetosphere with a plasma cloud which often follows the interplanetary shock. The forced reconnection of geomagnetic and interplanetary field lines, enhancement of magnetospheric

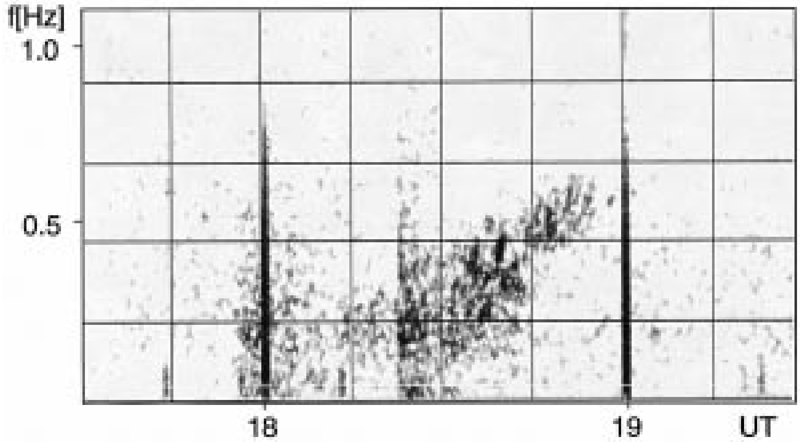

Figure 8. An IPDP associated with SI. The event was recorded in Sodankylä on August 25, 1978. SI occurred at 18:22 UT.

convection, spontaneous reconnections and explosions in geomagnetic tail, injections of energetic particles deep into the magnetosphere, growth of so-called ring current and progressive depression of geomagnetic field are the salient features of this interaction. During the main phase PiB, PiC and Pc2 pulsations are excited in the night, dawn and noon sectors, respectively. In the evening sector the intervals of pulsations of diminishing period (Ipdp) often appear. These frequency-modulated pulsations are the most prominent wave manifestation of the processes of ring-current formation. Pc1 pulsations are a rare phenomenon on the ground during the main phase of magnetic storm.

3.1. Pulsation Signatures of Magnetic Reconnection

Quasi-stationary magnetospheric convection is characterized by the large-scale electric field $E \sim 0.5$ mV m^{-1} directed from dawn to dusk. Corresponding potential across the geomagnetic tail is of the order of 100 kV. The tail is in a metastable state with a great amount of accumulated energy. The margin of stability depends strongly on the magnetic field component which is perpendicular to the neutral sheet, and reasonably large in a neighbouring part of the tail at least.

During magnetic storm the situation changes. The convection builds up and the magnetic energy of the tail rises to higher values whereas the stability margin of the tail goes down. Eventually these processes lead to a violent conversion of the accumulated magnetic energy to heat, mechanical energy and electromagnetic waves via the spontaneous reconnection of magnetic field lines. Explosions of this kind (substorms) may occur over and over again in the course of the main phase of geomagnetic storm; the greater the number of substorms, the stronger the ring current and the greater the storm-time magnetic variation (Akasofu and Chapman, 1972; Nishida, 1978).

The substorm as a building block of the main phase of a geomagnetic storm has a clearly defined pulsation structure (Akasofu, 1968). The PiB is the very first pulsation signature of the magnetic field line reconnection in the geomagnetic tail. Figure 2(b) gives an indication of the dynamic spectrum of specific PiB $\rightarrow$ PiC sequence. PiB's are defined as broadband impulses. The long-period ($T = 40$–150 s) and short-period ($T = 1$–40 s) parts of the impulse are usually specified by abbreviations Pi2 and Pi1B, respectively (Saito, 1969; Kangas et al., 1979; Bösinger and Wedeken, 1987). (In the scope of the present review we deal only with the Pi1B part of PiB.) The duration of PiB's is $\sim$2–3 min. Impulses have a maximum intenslty in the auroral zone near local midnight, and they tend to appear in a group or cluster of 3–5 impulses at 3–10 min intervals. Pulsations of this type reveal a strong correlation with the intensity of aurora, bursts of X-rays in the stratosphere, ionospheric absorption of cosmic radio noise, and other related phenomena (e.g., Bösinger et al., 1981; Yahnin et al., 1983). It is evident that all these phenomena including PiB pulsations are the transient response of the ionosphere-magnetosphere coupled system to the injection of energetic particles from the neutral sheet into the magnetosphere at the substorm onset (Baumjohann and Glaßmeier, 1984; Samson, 1991).

PiC pulsations appear in the night and morning sector of the auroral zone in the wake of PiB. Troitskaya et al. (1973) observed an eastward movement of PiC structural elements with angular velocity of $\sim$1.2 deg min^{-1}, suggesting that the source of these pulsations is connected to the eastward drift motion of injected electrons. Similarly, it would appear reasonable that the Ipdp pulsations in the evening hours after PiB (Figure 2(c)) are associated with energetic protons which drift to the west from the injection area. We reserve the problem of Ipdp to the next subsections. Here, let us pursue our discussion of PiB pulsations in more detail. (Recall that Pi1B is lettered here by PiB for the sake of brevity.)

It should be noted that Pi2's are traditionally used as a substorm timer, i.e., as an indicator of substorm onset and intensifications (e.g., Saito, 1969; Rostoker and Olson, 1978). A careful study of PiBs shows that the fine structure in temporal development of these pulsations correlates well with Pi2's signatures and auroral activity, and therefore PiBs may be also used as a high-time-resolution monitor of substorm development (Bösinger et al., 1981; Bösinger and Yahnin, 1987; Yahnin et al., 1990).

In Figure 9 the dynamic spectra of the records at SJU (Sjursnes, $L = 6.2$) and GRU (Grubenhagen, $L = 2.3$) are presented (Bösinger and Wedeken, 1987). We can see that the onset of PiB at 22:10 UT of both components occurred simultaneously at both stations despite the fact that the amplitude of pulsations at high latitude station far exceeds the amplitude measured at midlatitude one. Simultaneous occurrence of PiB with a rather sharp front over the wide range of latitudes in the nightside hemisphere makes PiBs useful in substorm timing procedure.

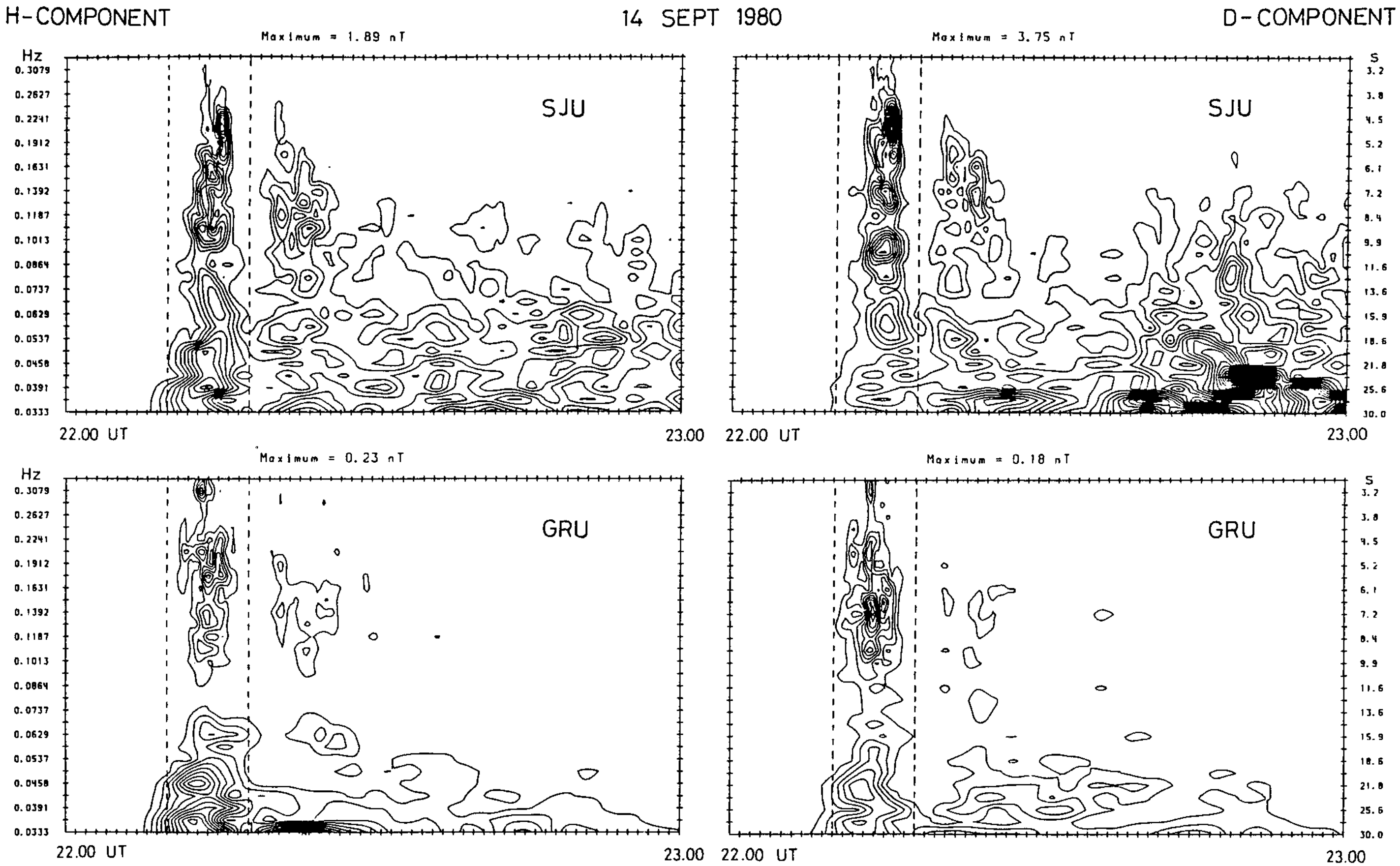

Figure 9. Dynamic spectra of Pi1 type magnetic pulsations observed simultaneously at high latitude (SJU) and midlatitude (GRU) station (after Bösinger and Wedeken, 1987).

3.2. Morphology of Ipdp

Ipdp, or geomagnetic pulsations of rising frequency, have attracted considerable interest since its discovery in the late 1950s. This interest comes largely from the idea that the proper understanding of Ipdp might help to solve the problem of initiation and evolution of the Earth's ring current (RC), in so far as it is generally agreed that these pulsations are caused by a resonant instability of energetic ions in RC. (e.g., Troitskaya, 1964; Gendrin et al., 1967; Heacock, 1967; Troitskaya and Guglielmi, 1967; Fukunishi, 1969; Kangas et al., 1974, 1976; Nishida, 1978; Fukunishi et al., 1981; Pikkarainen, 1987; Samson, 1991; Hayakawa et al., 1992a; Guglielmi and Pokhotelov, 1996).

Ipdp-type pulsations stand out sharply against the other waves because of their well-defined frequency modulation. Within about half an hour the midfrequency increases from fractions of Hertz to $\sim$1 Hz (see Figure 2(c)). The mechanism for this frequency growth is the key problem in the Ipdp theory (see Subsection 3.3).

The amplitude of oscillations is of the order of 0.1–1 nT with maximum in evening sector of subauroral zone. According to Pikkarainen (1987), the majority of Ipdp events occur between 15–21 LT. The mean onset time of the Ipdp at the Finnish meridian is 17.20 LT at auroral latitudes and a little later at lower latitudes. Most of Ipdp events occur when Kp is between 2–5 (Figure 10). With increasing Kp-index Ipdp events are displaced towards earlier local times and lower latitudes. We note also that Ipdp is most frequently generated when the AE index is between 300–900 nT. Usually Ipdp is preceded by a sharp negative bay in the midnight sector but is associated with a positive bay in the afternoon-evening sector (Heacock, 1967, 1971; Fukunishi, 1973). Ipdp event is often preceded by Pi1B, indicating impulsive injection of energetic particles from the tail plasma layer into the magnetosphere in the vicinity of the midnight meridian.

The typical frequency drift (Ipdp $f - t$ slope) $\mathrm{d}f/\mathrm{d}t \sim 1$ Hz hr^{-1}, but it depends on latitude, longitude, and on the level of geomagnetic activity. E.g., Pikkarainen (1987) has shown that the $f - t$ slope depends dramatically on Kp (see Figure 11). We see also that although the slope does not depend on latitude for low Kp, during more active periods it becomes steeper as the L-value of the observing station decreases.

Fukunishi (1969), Maltseva et al. (1970), Lukkari et al. (1975), Fraser and Wawrzyniak (1978), and Pikkarainen et al. (1983) have investigated the azimuthal development of Ipdp events. The main result is that a given frequency ω = const is observed at the eastern observatories earlier than at the western ones. We may say that the frequency ω 'travels' along the azimuth from east to west with the velocity of the order of $\sim$2–5 deg min^{-1}. Figure 12 illustrates the situation. The velocity of western drift at frequency 0.6 Hz is 2.6 deg min^{-1} between Irkutsk and Nurmijarvi and 1.4 deg min^{-1} between Nurmijarvi and Lervick. One more example of the longitudinal dependence of spectral evolution is shown in Figure 13. The geomagnetic coordinates of observatories are as follows: Tixie Bay (65.6 N,

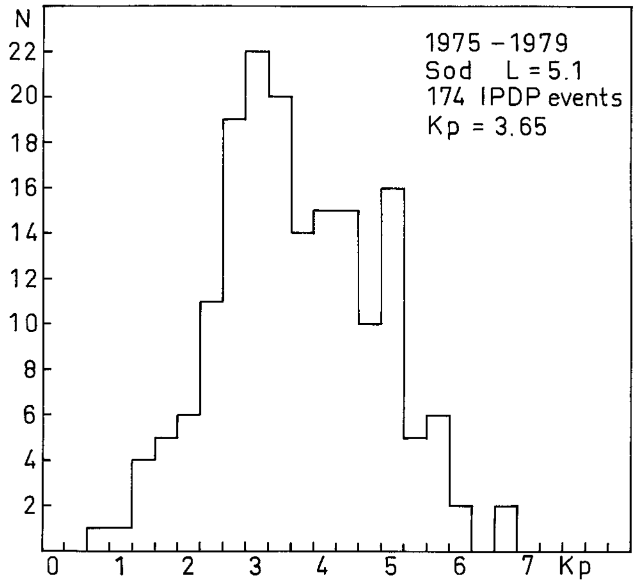

Figure 10. Distribution of IPDP events observed in Sodankylä in 1975–1979 by Kp (after Pikkarainen, 1987).

194.9 E), Chokurdakh (65.5 N, 210.1 E), Cape Schmidt (64.4 N, 234.2 E). The slope of the event becomes significantly smaller at more western stations, which could not be identified in Figure 12 (Pikkarainen et al., 1983).

Kangas et al. (1974, 1976, 1988), Lukkari and Kangas (1976), Lukkari et al. (1977), Pikkarainen et al. (1983), and Pikkarainen (1987) presented a thorough investigation of Ipdp's based on the data from the Finnish north-south magnetometer and riometer chain, which were supplemented by the electric data from the EISCAT incoherent scatter radar. The main result is that the oscillation frequency increase is obviously associated with the radial drift of the emitters towards the Earth under the action of the magnetospheric large-scale electric field. Typical examples of the southward motion of Ipdp amplitude maximum and associated riometer absorption in the course of an event are presented in Figures 14 and 15. On the relative role of the radial and azimuthal drift of the emitters see also the papers by Heacock (1973), Heacock et al. (1976), Fraser and Wawrzyniak (1978), Arnoldy et al. (1979), and Maltseva et al. (1981).

Pikkarainen et al. (1983) and Pikkarainen (1987) showed in their investigations of ground-based observations that the frequencies of Ipdp events are lower than the He+ gyrofrequency at the corresponding field line in the equatorial plane. In Figure 16 we see that the end frequencies are mainly between He^+ and O^+ gyrofrequencies. This observation shows that the end frequency of Ipdp depends on the L value, as well as that the heavy ions in the magnetosphere control the frequency band of pulsations recorded on the ground.

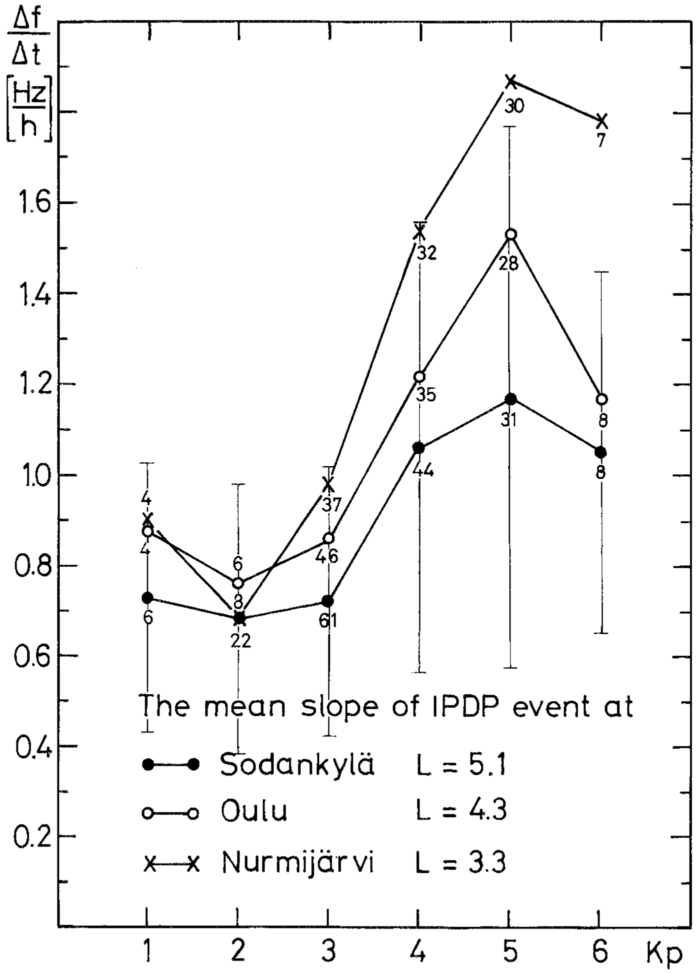

Figure 11. The slope of IPDP at three Finnish stations as a function of Kp (after Pikkarainen, 1983).

A special type of Ipdp wave events was discovered by Fukunishi and Toya (1981). These oscillations appear in the morning hours and not in the evening sector. The frequency range of the morning Ipdp is 0.1–0.6 Hz, and the frequency drift is 0.2–1 Hz h^{-1}. The dynamic spectrum consists of discrete irregular elements. In contrast to ordinary ones, morning Ipdp's appear most frequently under weak or moderate magnetic activity.

IPDP type plasma events have been observed only very seldom in the magnetosphere. Perraut et al. (1978) have reported that four such events have been identified in GEOS 1 satellite recordings. An example together with the ground observations in the northern conjugate area is shown in Figure 17 (courtesy of Dr Perraut and Dr Pikkarainen, see Pikkarainen, 1989).

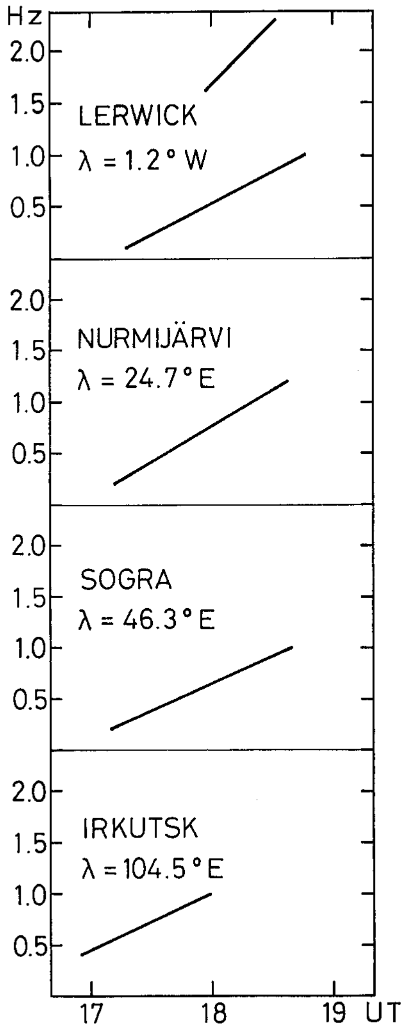

Figure 12. Schematic presentation of IPDP's observed at four meridians January 31, 1975 (after Pikkarainen et al., 1983).

GEOS 1 foot point was 15 deg to the west from the Finnish meridian on June 2, 1977 when an IPDP was recorded. When the satellite descended from $L = 5.7$ to $L = 5.0$ in the time interval 18:40–19:13 UT the frequency of the observed waves increased from 0.25 Hz to 0.60 Hz. These frequencies are below the local gyrofrequency of He^+ ions. At the same time an IPDP extending from 0.20 Hz to 0.60 Hz was detected on the ground at Oulu ($L = 4.3$). The same event was recorded also at Sodankylä ($L = 5.1$). These measurements demonstrate that the IPDP observed at a single ground station can be a composition of waves originating from magnetospheric sources at different L-shells. This interpretation explains why

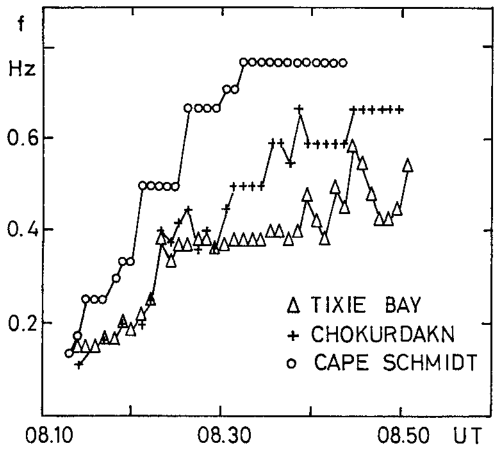

Figure 13. The frequency as a function of time for the IPDP event observed on March 15, 1976 at three sites that are at about the same latitude. The longitudinal separation of the furthermost stations is 40° (after Pikkarainen et al., 1983).

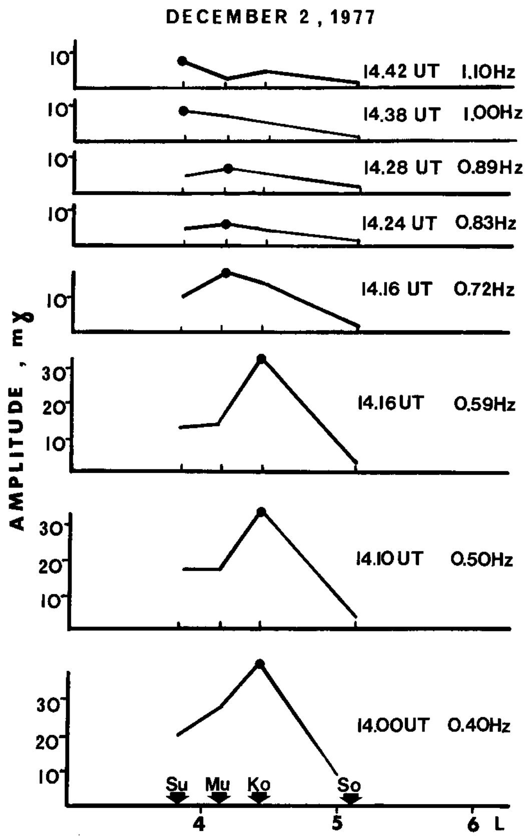

Figure 14. Temporal development of the latitudinal amplitude profile of IPDP pulsations observed on December 2, 1977 (after Maltseva et al., 1981).

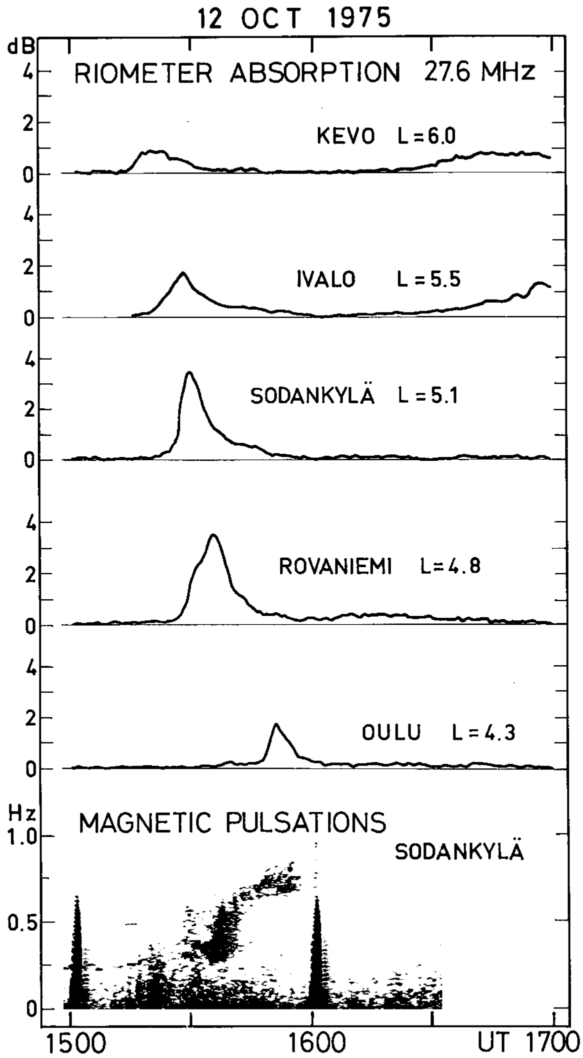

Figure 15. Correlated riometer absorption and IPDP events observed at the Finnish net of stations on October 12, 1975 (after Pikkarainen et al., 1986).

Pc1 pulsations are usually observed by the geostationary satellite when an IPDP develops in the conjugate ground area (Bossen et al., 1976; Fraser and McPherron, 1982).

Particle measurements in the magnetosphere show that energetic protons are associated with the generation of IPDP type pulsations (Horita et al., 1979; Soraas et al., 1980). According to Horita et al. (1979) only the protons in the energy range of 40–60 keV seem to be efficient for the generation of ion cyclotron waves during

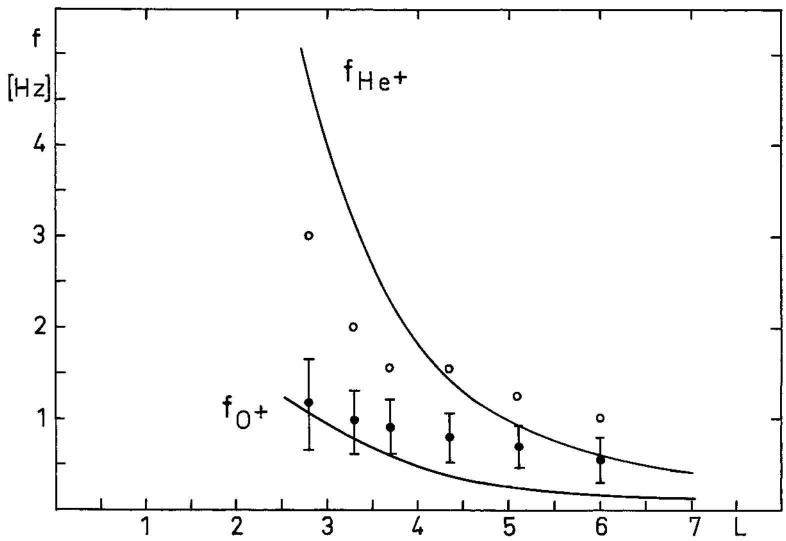

Figure 16. The average end frequency in IPDP observed at different L values (black dots). Open dots refer to the highest IPDP end frequency recorded at a given latitude. Curves represent the variation of the O^+ and He^+ gyrofrequencies in the equatorial plane (after Pikkarainen, 1987).

IPDP. Anisotropic fluxes of protons around 35 keV have been measured by GEOS 1 during the IPDP event shown in Figure 17.

3.3. The models of IPDP

Particular interest in Ipdp is evidently connected with their prominent temporal evolution, distinguishing Ipdp from other pulsations. At the same time, Ipdp's are in some respect similar to Pc1, as will be discussed later in Subsection 3.4. It is reasonable that we try to understand the nature of Ipdp by using the ideas which have been so far proposed by many authors in attempting to understand Pc1. In doing so, we reduce the problem to the search for mechanisms of the specific frequency modulation.

In the 1960s the mechanism of frequency modulation in the course of Ipdp magnetic pulsation event has been the subject of intensive and controversial literature. Jacobs and Watanabe (1962) made the first attempt by explaining the increase in pulsation frequency by a decline of the ionospheric plasma density, based on the belief that the ionosphere is a selective filter which passes a band of the spectrum of magnetospheric noise. Although the idea is interesting as such, it does not apply at least in general since it is in conflict with the morphological evidences, in particular with the good correlation of Ipdp spectra measured simultaneously in conjugate areas (Gendrin and Troitskaya, 1965).

The good conjugacy of Ipdp suggests a magnetospheric mechanism of the frequency modulation. Based on the resonance relation like (11), it has been spec-

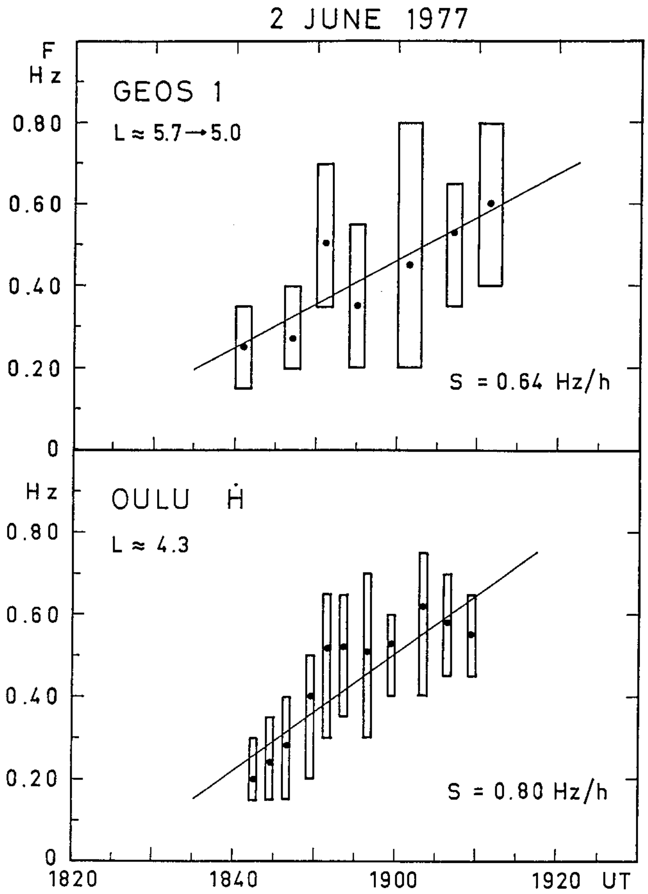

Figure 17. Dynamic spectra from ULF wave recordings at GEOS 1 satellite and at ground station Oulu, about 15 deg to the east from the satellite conjugate point. Straight lines represent average slopes of increasing frequency. (From the courtesy of Dr S. Perraut and Dr T. Pikkarainen, see also Pikkarainen, 1989.)

ulated that the increase in pulsation midfrequency results from the enhancement of magnetic field in the region of generation and/or decrease in energy of resonant particles. In principle, it is also possible that a decrease in plasma density produces the phenomenon, but it is likely to be of no importance for Ipdp.

Kozlowski (1963), Guglielmi (1968), and Roxburgh (1970) associated the increase of pulsation frequency $\omega(t)$ with enhancement of geomagnetic field $B(t)$ at the fixed L value near the maximum of intensity of the ring current particles. In a concise form the idea is as follows. The ion-cyclotron instability of RC leads to excitation of pulsations which in turn leads to a decrease in RC intensity due to the pitch-angle scattering of energetic particles. As a result, the depression of geomagnetic field diminishes, and a strong drift of oscillations in frequency arises due to the fact that the resonance frequency ω depends on B^2 (see Equation (11)).

In this explanation there is, however, some good experimental evidence against it. The variation in RC intensity leads to perturbations of the geomagnetic field which have opposite signs inside and outside the central part of RC. Hence, in this way we can expect pulsations of rising as well as falling tones. Such observations do not exist. (These considerations can be applied to the model of Ipdp based on the hypothesis of modulation by the ionosphere as well.)

Heacock (1967) and Gendrin et al. (1967) independently proposed the mechanism of cyclotron instability of RC ions drifting toward the Earth across the magnetic shells under the action of a large-scale electric field E. Since $\omega \propto B^2$ and $B = B[L(t)]$, then $\dot{\omega} \propto (\partial B/\partial L)\dot{L}$ and

$$\mathrm{d}\omega/\mathrm{d}t \propto E \tag{24}$$

in so far as $\dot{L} \propto E$ (Troitskaya et al., 1968). The experimental verification of relation (24) with corresponding coefficient of proportionality has given quite good results (Lacourly, 1969; Heacock et al., 1976; Kangas et al., 1988). Nonetheless, this model is not fully satisfactory because it leaves unexplained the appearance of Ipdp in the evening sector. In particular, if E is the large-scale electric field of magnetospheric convection (directed from dawn to dusk) then the radial drift is absent in the evening sector since the electric drift velocity has no radial component there.

That is not to say that the inward cross-L drift of the Ipdp source is absent. After the experimental works by Kangas et al. (1974), Heacock et al. (1976), Lukkari et al. (1977), Soraas et al. (1980), and Pikkarainen et al. (1983) (see Subsection 3.2), there is no doubt that the source of Ipdp exhibits the progressive radial displacement toward the Earth across the magnetic shells in the course of pulsation events. There is no doubt also that the large-scale electric field has a dominant role in this process. We shall return to this problem after a short presentation of another model which is based on the idea of azimuthal drift of the Ipdp source.

The idea of the spreading of a proton cloud during azimuthal drift as being the cause of the increase of the oscillation frequency during IPDP is due to Fukunishi (1969). As a test to verify his model Fukunishi used the dependence $\dot{\omega}(\Delta t)$ on the length of time interval $\Delta t = t_a - t_i$ between the time t_a of the appearance of Ipdp and the time t_i of the particle injection. Maltseva et al. (1970) detected independently the effect of the 'western frequency drift', as it is called, which is also an indication of the azimuthal drift of the source as being the cause of the frequency modulation. Indeed, let us suppose that the injection of particles near midnight meridian $\varphi = 0$ occurs at $t = 0$. Here φ is the azimuth counted westwards from the place of injection. The injected protons drift towards the evening sector with the velocity which is proportional to their energy ε, i.e., $\dot{\varphi} \propto \varepsilon$. This leads to estimation of the typical energy $\varepsilon \approx \varphi/t$ and frequency $\omega \propto \sqrt{t/\varphi}$ at the given values φ, t when taking into account the resonance condition (11) and the relation $w = \sqrt{2\varepsilon/m}$. For good reason this model will be named as WPF ('Wave-Particles Fan') model.

Hence, in the frame of the WPF model the frequency modulation of $\omega \approx \sqrt{t}$ is the result of spreading of the cloud of injected protons in the course of their azimuthal drift. The dependence of the steepness of the frequency rise in IPDP on φ has the form

$$\mathrm{d}\omega/\mathrm{d}t \approx \varphi^{-1} . \tag{25}$$

WPF model has a good experimental status (e.g., Fukunishi, 1969; Maltseva et al., 1970; Fraser and Wawzyniak, 1978; Pikkarainen et al., 1983, see also Subsection 3.2), and in addition to that, successful linear theories have been developed on the basis of this model (e.g., Lin and Parks, 1976; Guglielmi and Zolotukhina, 1983). Nevertheless, WPF model needs an essential modification since it fails to explain the most important property of Ipdp, namely, the cross-L drift of the source. In the review by Samson (1991) it is said that '... the rising frequencies are probably caused by the westward drift of the protons, with progressive earthward penetration of the protons'. Hayakawa et al. (1992a) have advanced the construction of a combined model for the description of the frequency modulation by taking into account both radial and azimuthal drifts of energetic particles after an impulsive injection during substorm (see also Soraas ct al., 1980; Pikkarainen et al., 1986).

However, we have yet another difficulty which at first sight is unrelated to the problem of cross-L drift. According to Kangas et al. (1976), in some instances Ipdp may appear as an extension of Pc1-2 waves. It means that Pc1-2 pulsations with quasi-stationary spectrum merge more or less continuously into Ipdp. Should this be the case then the source of both Pc1-2 and Ipdp pulsations exists for a more or less extended time *before* the injection of particles associated with substorm onset. (See also the following subsection.) If so, can the rising frequency in an Ipdp event be understood in the frame of the WPF model? In the case of Ipdp observed near the geomagnetic poles (Shchepetnov and Kalisher, 1968; Lanzerotti, 1978; Fraser-Smith, 1982) the WPF model does not work either.

In a new model of the frequency modulation we emphasize the relationship between Ipdp and large-scale electric fields of magnetospheric convection. According to Rutte et al. (1978) there is a 'distinction between polar magnetic substorms and convection driven negative bays' (see also Sergeev and Tziganenko, 1980). In other words, there exist two types of polar magnetic disturbances. Because of this one is inclined to think that there are at least two varieties of Ipdp, namely, 'injective' and 'convective' ones. (It should be realized of course that the real event may be a mixture of both types.) Here we describe in brief terms a qualitative model which seems to explain not only the frequency modulation as a result of the radial drift of generation region under the action of large-scale electric field, but also the Ipdp generation in the evening sector. An additional feature of this model is that it may be checked by experiment. The following notes are only intended to outline this so called WPB ('Wave-Particle Boiler') model as an alternative or, more precisely, as a complement to the WPF model.

As Troitskaya et al. (1968), we also start with the equation of type

$$\omega \approx (c_{\mathrm{A}}/w)\Omega\ , \tag{26}$$

where $\omega \ll \Omega$. This is the resonance relation for cyclotron instability and Cherenkov instability of ions with anisotropic and nonmonotonic distributions, respectively. The former is evident, the latter was considered by Guglielmi and Zolotukhina (1983). This note is important since the formation of nonmonotonic ion distribution is most typical of the evening sector. The action of the corresponding mechanism is based on the separation of ions by energy in the course of electric drift in the inhomogeneous magnetic field. Since the velocity of the gradient drift depends on energy whereas that of the electric field drift does not, the area of penetration for ions of different energies is different, and a nonmonotonic distribution may be obtained without any special assumptions about the source of particles. A source of ions with energy spectrum broad enough at the periphery of the magnetosphere is the only requirement.

In contrast to Troitskaya et al. (1968), we consider a more complex model of the large-scale electric field. The convection electric field E is assumed homogeneous and directed from dawn to dusk. In addition, we shall take into account the corotation electric field which is directed radially (towards the Earth) and is equal to the modulus $\Omega_\oplus M_\oplus/cr^2$, where $\Omega_\oplus$ is the angular velocity of the Earth's rotation, $M_\oplus$ is the magnetic moment of the Earth, r is the geocentric distance. The electric field E and energy ε are conveniently measured in the units $\Omega_\oplus M_\oplus/cR_\oplus^2 = 14.4$ mV m^{-1} and $e\Omega_\oplus M_\oplus/cR_\oplus = 92$ keV, respectively. Here $R_\oplus$ is the Earth's radius, e is the elementary charge, c is the velocity of light. Then the plasmapause position at 18 LT is determined by the relation (Nishida, 1978)

$$L_p = 1/\sqrt{E}\ . \tag{27}$$

A well-known fact fundamental to the WPB model is the penetration of ions with appropriate energies from the plasma sheet to the evening sector of plasmasphere, i.e., to $L < L_p$. Moreover, a 'wedge-shaped' nonmonotonic structure of energy spectrum of protons is formed in the evening sector. The 'edge' L' of the wedge penetrates inside the plasmasphere and the distribution function near 'edge' has the form $\sim \delta(\varepsilon - \varepsilon')$ with

$$\varepsilon' = a\sqrt{E}\ , \qquad L' = \frac{b}{\sqrt{E}}\ , \tag{28}$$

where $a \approx 1.2$, $b \approx 0.4$ (Guglielmi and Pokhotelov, 1996). The 'wedge-shaped' structure of the proton distribution in the evening sector was observed by Explorer-45 satellite (Smith and Hoffman, 1974). By using the measured parameters ($\varepsilon' \approx$ 17 keV, $L' \approx 4.6$, $L_p \approx 4.9$) we can estimate $a_{\mathrm{exp}} \approx 0.9$, $b_{\mathrm{exp}} \approx 0.9$. Hence the theory leads to an overestimate and underestimate of the coefficients a and b, respectively. This is of little consequence in a qualitative study of an Ipdp-electric field relation.

In summary, the periphery of the dusk-side plasmasphere contains permanently a population of energetic ions with nonmonotonic distribution. One would expect that the distribution is anisotropic as well. If the density of population is big enough, wave-particle interaction leads to the Cherenkov and/or cyclotron instabililies with self-excitation of MHD waves. The nonlinear interaction of waves with energetic ions and with each other brings the periphery of dusk plasmasphere to a turbulent state (wave-particle boiler or WPB). The main properties of WPB are as follows: (1) localization in the evening sector just inside the plasmapause, (2) wave-particle turbulence due to instabilities, (3) strong dependence on the dawn-dusk electric field.

Let us return to the discussion of the events where the appearance of Ipdp is preceded by Pc1-2 pulsations. Our hypothesis is that the Pc1-2 and subsequent IPDP are the two wave manifestations of operation of the common magnetospheric subsystem, namely, the wave-particle boiler. The increase of magnetospheric convection electric field corresponds to transition from Pc1-2 to Ipdp. Setting $\Omega \propto L^{-3}$, $c_{\mathrm{A}} \propto L^{-3/2}$ and using Equations (26) and (28), we obtain the dependence of pulsation frequency on the electric field of magnetospheric convection:

$$\omega(t) \propto E^2(t) \ . \tag{29}$$

Hence, the theory predicts that $\mathrm{d} \ln \omega = 2 d \ln E$. This relation can be verified by simultaneous observations of Ipdp magnetic pulsation events and variation of the large-scale electric field.

3.4. Comparative analysis of Pc1 and Ipdp

The known theories of Pc1 and Ipdp have much in common. It is suggested that the source of both types of pulsations is located in the equatorial plane of the geomagnetic shells with $L = 3...6$. The free energy is accumulated in energetic ions with non-equilibrium distribution of velocities. The mechanism of generation is the kinetic instability in both cases. The pulsations propagate from the source to the Earth along geomagnetic field lines.

At the same time, we know from experience that these two types of pulsations vary in morphology, and therefore, the question is raised: How do we understand the distinct properties of Pc1 and Ipdp? There is no complete answer to this long-standing question, but the subsequent discussion tries to clarify the present state of the art to gain a better insight into the mechanisms of these pulsations.

It is evident that the first and the most prominent distinction between Pc1 and Ipdp is in the character of frequency modulation. The accepted explanation calls for the quasi-stationary regime of excitation of the former type of pulsations, and the nonstationary regime of the latter one. The second difference is in the bandwidth of excitation. The relatively narrow frequency band of Pc1 is most likely conditioned by a small overbalance exceeding the threshold of stability. Hence, it is natural to think that the wide band of Ipdp is the wave manifestation of a more pronounced exceeding of the threshold.

The last hypothesis needs to be clarified. Indeed, on one hand the pulsation amplitude is proportional to the square root of supercriticality (see Equation (6), and on the other hand the observed amplitudes of Pc1 and Ipdp are of the same order (Saito, 1969). Perhaps, this conflict provides an insight into the nature of Pc1 and Ipdp. Before proceeding further in this direction, we consider one more distinction between the two types of pulsations.

Structured Pc1 events are characterized by the repetitive structure which is absent in general in Ipdp events. There is a need to explain the latter, since the former is reasonably explained by ducting of the Pc1 wave packet along geomagnetic field lines with amplification at the top of trajectory, reflection from the ionosphere, and formation of the succession of echo-signals (for further discussion, see Subection 4.2). The problem is open to speculation. As the first step, we can do no more than to mention the non-stationarity of the Ipdp source. One may conclude that the non-stationarity of the amplification band hinders the formation of any prolonged repetitive wave structure. One might discuss here the origin of dispersion of the Pc1 structural elements, but this problem has been discussed in detail by Nishida (1978) and Samson (1991).

We return to our previous note about the amplitudes and thresholds of stability. The following arguments may resolve this contradiction.

The energetic ion flux during a magnetic storm is so strong that the excitation of Ipdp does not need positive feedback. In the case of Pc1 this is produced by the wave reflection from the waveguide ends and return of the waves to the amplification region. During Ipdp excitation, the magnetosphere is possibly in the state of absolute instability or (in the case of convective instability) the amplification is so strong that the wave amplitude increases up to observable values within one pass through the amplification region. Thus, our hypothesis is that the Pc1 and Ipdp are excited as a result of global and local instabilities respectively, and therefore the direct correspondence between their amplitudes may be absent.

After all it seems likely that Pc1 and Ipdp may be classified as a single group. If so, it is expected that there exists an intermediate subclass of pulsations, in which the most prominent properties of Pc1 and Ipdp are seen in the same event. Such an example is shown in Figure 18. A Pc1-Ipdp sequence was observed in December 1984 at Oulu ($L = 4.3$). Pearl-type Pc1 pulsations are seen before the onset of the substorm at 20:38 UT as indicated by a PiB. In 20:15–20:28 UT the Pc1 midfrequency increases as is typical for IPDP. The IPDP after the onset of the substorm exhibits structural repetitive elements typical for Pc1 pulsations.

This event is of additional interest in two respects. Firstly, we see a gap or fading (stopped beating) of pulsations at Kevo for 15–20 min before the onset of the substorm. Secondly, the increase in Pc1 midfrequency starts at least 15 min before the substorm onset. We think that both effects are due to an enhancement of the electric field of magnetospheric convection, which led to explosions in geomagnetic

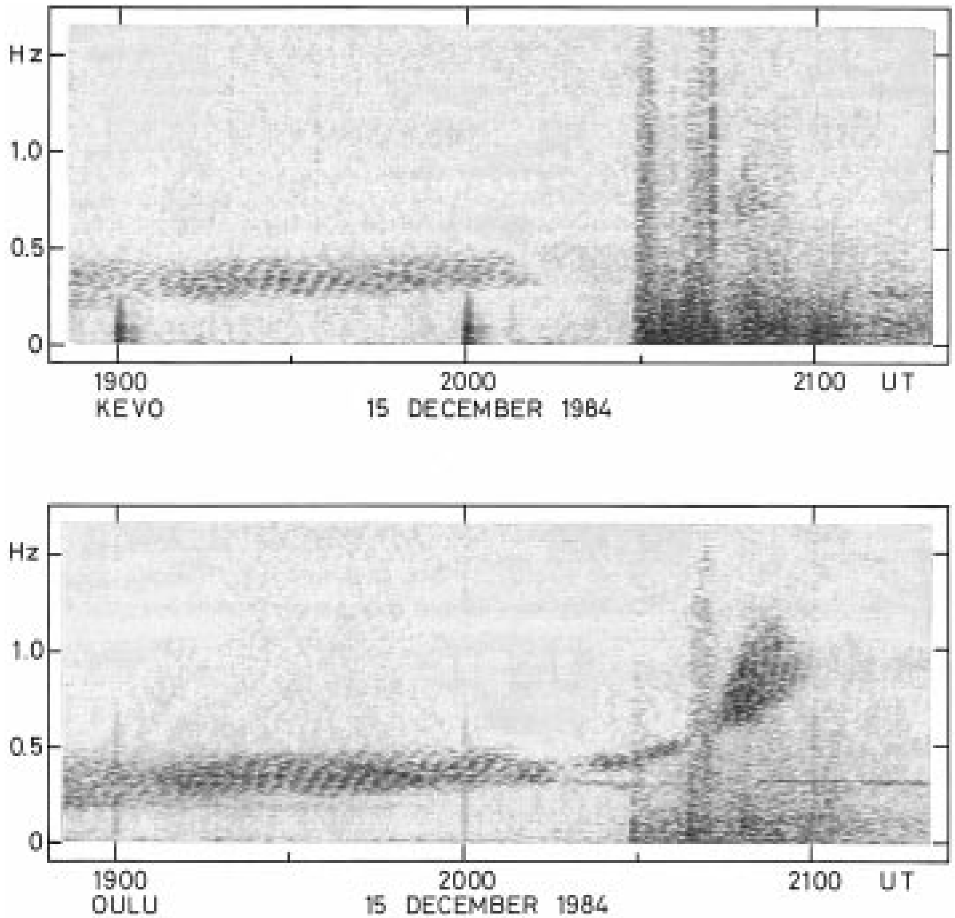

Figure 18. Dynamic spectra of magnetic pulsation recordings made at Kevo and Oulu stations on December 15, 1984.

tail, injections of energetic particles deep into the magnetosphere, and generation of PiB $\rightarrow$ Ipdp sequency. The change in the regime of magnetospheric convection led to a change in conditions for generation and/or propagation of Pc1 waves.

3.5. Two possible mechanisms for the production of Pc2

The frequency of Pc2 varies in a range of only one octave (0.1–0.2 Hz). These pulsations 'close' the spectral gap between Pc3 (0.022–0.1 Hz) and Pc1 (0.2–5 Hz) which span more than two and four octaves, respectively. It would appear natural that Pc2's do not form a homogeneous class, but they are a mixture of two varieties, one of them is akin to Pc1 and other to Pc3. We shall advance the arguments in favor of this hypothesis.

The flow of H^+ ions in the magnetosphere is considerably in excess of the flow of O^+ ions in relatively quiet periods. During magnetic storms, however, the opposite situation may occur (Balsiger et al., 1980). It is just in these disturbed periods that Pc2's are seen in middle latitudes. This suggests that Pc2's are excited in the radiation belt by oxygen ions during the main phase of a magnetic storm, in the same way as Pc1 pulsations are excited by protons during the recovery phase (see the following section). Indeed, according to the resonant condition (11) $f \propto m_i^{-1/2}$, all other factors being the same. Here m_i is the mass of resonant particles. 'The other factors' are local magnetic field, local Alfvén velocity, and the energy of resonant particles. Therefore, formally the usual Pc1 band transforms to the band 0.05–1.25 Hz when H^+ is replaced by O^+. This new band overlaps the Pc2 frequency band, suggesting that these pulsations are the ion-cyclotron waves which are excited by oxygen ions. This point of view was indirectly confirmed by the comparison of ground magnetograms of Pc2 with the satellite measurements of the energetic O^+ fluxes (Kalisher et al., 1982). An additional argument is as follows. According to Young et al. (1982) the maximum abundance of O^+ in the magnetosphere is observed in the years of solar cycle maximum, and the long-time behaviour of Pc2 is characterized by the maximum rate of occurrence in the same years (see Section 5).

However, the correlation of Pc2 with increased O^+ fluxes does not eliminate another possibility for Pc2 appearing at mid-latitudes during magnetic storms. It cannot be ignored that Pc2 waves may penetrate into magnetosphere from the upstream region, just like Pc3. This possibility has already been discussed at the end of Section 2. So, we know two possible mechanisms of Pc2 generation, however, the phenomenon is still not completely understood. The method of $f - B$ diagram, as it is called, seems to demonstrate the dual origin of Pc2 (Guglielmi et al., 1989), but the direct proof is absent.

The issue is complicated by the fact that Pc2's are observed sometimes in geomagnetically calm periods. These pulsations with amplitudes up to 0.2 nT appear in the polar caps at Kp $\sim$ 1–2 (Bolshakova and Guglielmi, 1972). Their origin remains unsolved.

4. Recovery Phase of Magnetic Storm

The damping of a geomagnetic storm may last from a few hours to some days. It is characterized by the decay of the ring current, attenuation of magnetospheric convection, and also by the plasmasphere refilling. In this period, called the recovery phase of magnetic storm, PiB impulses continue to appear in the night side of the Earth, but their intensity weakens. The activity of Pc2 pulsations falls off, and permanent Pc3 oscillations lasts from morning till night. Their period gradually increases. It is during the recovery phase when a great number of Pc1 'pearl' series is usually observed. It may be said that the excitation of pearl pulsations is the most long-lasting after-effect of the magnetic storm.

4.1. Excitation of Pc1, plasmaspheric refilling, and decay of the ring current

We focus our attention on the appearance of a large body of Pc1 series in the recovery phase. There is an interconnection between the excitation of Pc1, plasmaspheric refilling, and decay of the ring current. In order to fully recognize this interconnection we must take a closer look at the relaxation processes in the magnetosphere after the shutdown of the source feeding the ring current.

The key role is played by the attenuation of the large-scale electric field of magnetospheric convection. To illustrate this we shall consider qualitatively a simple case of a steep decrease in the intensity of large-scale field E. As E is diminished, the corotation region is expanded since the position of critical point L_c of the separatrix is proportional to $E^{-1/2}$. The establishment of equilibrium between the plasmapause position L_p and the new position of separatrix L_c is referred to as plasmaspheric refilling (Nishida, 1978). The process of refilling is rather slow, it may last for several days.

Hence, immediately after the drop of E, the distribution of background plasma looks much as it does before the drop. This means that there is a region of very low plasma density between the current plasmapause position L_p and its future position L_c. For example, if E changes from 1.2 mV m^{-1} to 0.5 mV $^{-1}$ then the gap extends from 3.5 to 5.5 Earth's radii. The dense plasma fills the gap gradually, with an outward-directed overall motion of the plasmapause. It is evident that the plasmaspheric refilling is the process responsible for the self-excitation of pearl geomagnetic pulsations, decay of the ring current and, as a consequence, for the recovery of the geomagnetic field after a storm (e.g., Thorne, 1974; Nambu, 1974).

The main idea is as follows. Kennel and Petschek (1966) put forward the concept of self-restriction of energetic ions in the radiation belt due to the excitation of ion-cyclotron waves, pitch-angle diffusion and the escape of particles into the loss cone. Based on this most important concept, known in the literature as the 'limit of stability of the radiation belt', Cornwall et al. (1970) suggested an explanation for the correlation of radial distribution of the ring current protons with the location of the plasmapause. It is evident that not only the distribution of background plasma but also the energy, which has been accumulated in the ring current, does not change immediately after a drop of the large-scale electric field. Let us suppose for simplicity that pulsations are absent after the decrease, i.e., the ring current particles have been in the state below the threshold of ion-cyclotron excitation before the drop. In other words, $\Lambda < \Lambda_c$ in the terms of Subsection 2.3, or $\lambda < 0$ where $\lambda = \Lambda - \Lambda_c$ by definition.

The onset of plasmaspheric refilling with overall outward displacement of the plasmapause can radically alter the state of the system. Namely, this displacement can transfer the system to an unstable state because the threshold Λ_c^- inside the plasmapause ($L < L_p$) is lower than Λ_c^+ outside ($L > L_p$). Calling $\lambda_c = \Lambda_c^- - \Lambda_c^+$, we can write the criterion $\lambda > \lambda_c$ for the development of the ion-cyclotron instability in the course of plasmaspheric refilling with $\mathrm{d}L_p/\mathrm{d}t > 0$. The growth of ion-cyclotron waves leads to a new 'limit of stability' with a lower level of ring current intensity.

Therefore, the decay time of the ring current is the smaller, the faster the plasmapause moves away from the Earth. The point is that the critical flux of energetic particles is larger outside the plasmapause than inside. Thus the outward motion of the plasmapause 'eats away' particles of the ring current and weakens the storm-time variation of the geomagnetic field.

It is pertinent to note that the jump λ_c of the threshold is due to the reduction of the wave losses in the waveguide at the plasmapause (see also Equation (17) and the subsequent text). The problems of waveguide propagation of ion-cyclotron waves will be considered in the following subsection. One more note is as follows: Pc1 pulsations play a certain active role in the process of plasmaspheric refilling. We shall return to this question in Subsection 6.2.

There is good indirect morphological evidence that the scenario outlined above reflects the real processes in the magnetosphere. Firstly, a large body of Pc1 series appears during the recovery phase of magnetic storms (Wentworth, 1964). Based on the study of 35 typical magnetic storms with SSC (Kerttula, Pikkarainen, and Kangas, private communication, 1997) discovered recently that the average time delay between the Dst minimum and the first Pc1 event on the ground is 18.5 hr in low sunspot years and 46.3 hr in high sunspot years. This difference may be due to a solar cycle variation of the threshold for self- excitation of ion-cyclotron waves in the magnetosphere (see also Section 5).

Secondly, ground-based observations show that pearl-type Pc1 wave series with decreasing mid-frequency are abundant in late recovery phase of magnetic storms (Offen, 1972; Matveyeva et al., 1972b; Dovbnya et al., 1974, see also Figure 3) . According to the resonance condition (11) this corresponds to the outward motion of the generation region. And thirdly, there are indications that Pc1 events appear at low latitudes early in the recovery phase, and later at high latitudes (Kuwashima et al., 1981). These facts support the view that the plasmaspheric refilling is indeed responsible for the excitation of Pc1 and for the decay of ring current.

4.2. Pearls in the Waveguides

In the mid-1960s the attempts to understand morphological properties of Pc1 led to the idea of waveguide propagation of these pulsations. Over the years the concept of hydromagnetic and ion-cyclotron waveguides in the ionosphere and magnetosphere has been of considerable importance in the investigation of Pc1 by ground-based and satellite methods. This question has been repeatedly and appropriately summarized in the literature. Here we only recall the basic facts about waveguide propagation of Pc1, underlining the unsolved problems.

Let us start with the ionospheric MHD waveguide where Pc1 pulsations travel along the Earth's surface over great distances (up to ten thousand kilometers) from the source. It was the global occurrence of Pc1 which gave the first indirect clue to the idea of horizontal propagation of Pc1 in the ionospheric layers (Tepley, 1965; Wescott et al., 1966). One more morphological property gives an additional reason to adopt the concept of ionospheric waveguide. Namely, it has been discovered that only the Pc1 pulsations with frequencies more than $\sim$ 0.5 Hz are observed simultaneously at widely spaced locations (Troitskaya, 1964). The presence of a limiting frequency in the spatial distribution of Pc1 is good indirect evidence that the pulsations propagate horizontally in a waveguide with the cutoff frequency $f_c \sim$ 0.5 Hz. And the last, but not least evidence is as follows: according to direct measurements by Wentworth et al. (1966), the velocity of horizontal propagation of Pc1 is of the order of 700 km s^{-1} (see also Selzer, 1959). This velocity corresponds approximately to the calculated velocity of magnetosonic waves in ionospheric layers. These three properties indicate that the waveguide propagation of Pc1 along the Earth's surface really occurs.

We elucidate the essence of the subject in terms of the ray theory of waves. Recall that the ray in a stratified isotropic medium bends towards increasing refractive index $n(z)$ or, in other words, the ray is convex in the direction of decreasing $n(z)$, where axis z is normal to the stratification. Therefore, the waveguide propagation, i.e., the finite motion of the rays along z is possible if the refractive index $n(z)$ has a maximum. The ionosphere can be considered nearly stratified, and the magnetosonic waves are almost isotropic with $n = c/c_{\mathrm{A}} \propto \rho^{1/2}$, where $\rho(z)$ is the plasma density, z is directed upward. Since $\rho(z)$ has a maximum at the altitude of $z \approx 300$ km, it may be expected that, in certain conditions, the rays of magnetosonic waves are captured by the ionospheric layers.

This consideration demonstrates a ducting of magnetosonic waves along ionospheric layers, however, with the ray approach we overlook several important features of the Pc1 wave field (penetration into the atmosphere, mutual transformation of magnetosonic and Alfvén modes in the lower ionosphere, and others). The waveguide mode approach to the problem was developed by Manchester (1966), Tepley and Landshoff (1966), Greifinger and Greifinger (1968), and Manchester and Fraser (1970). Fujita (1988) studied the waveguide attenuation due to Joule dissipation and mode conversion. He found that the Joule dissipation prevails over the conversion when the Pedersen conductivity of the lower ionosphere exceeds the Hall conductivity. If the Hall conductivity is sizably higher than the Pedersen one, then the mechanism of conversion is effective enough, and the frequency dependence of the waveguide attenuation has a quasi-periodic form. The theory as well as the observations testify that the waveguide attenuation changes from units to dozens of dB/1000 km, and in the daytime damping is considerably higher than at night. Fujita and Tamao (1988) investigated the excitation of the waveguide by a beam of Alfvén waves which is incident upon the ionosphere. Ovchinnikov (1991) developed an interesting approach to the problem by using a quasi-static series of even powers of the wavenumber below the maximum of the $F2$-layer.

The theory of the ionospheric MHD waveguide is widely used to explain the observed properties of Pc1, however, some development of theory is necessary to understand the following paradox. It seems likely that pulsations in the waveguide travel predominantly in the equatorward direction from the source rather than to the pole in spite of the fact that the horizontal projection of Alfvén rays which are incident upon the ionosphere has a poleward component. It is not inconceivable that this paradox is directly related to another problem, namely, that we need to take into account the horizontal inhomogeneity of the ionosphere in the solving of the field equations.

Next, we discuss an equally important, and no less difficult problem of Pc1 waveguide propagation in the magnetosphere. The very fact of the periodicity of the Pc1 wave packet repetition gives us an indirect clue to the idea of waves ducting along the geomagnetic field lines. (See the following subsection for a more detailed discussion about the repetition period.) The simultaneous observations of Pc1 at conjugate points give an additional argument (Yanagihara, 1963; Campbell and Stiltner, 1965; Gendrin and Troitskaya, 1965; Ishizu et al., 1981). The complete picture is that Pc1 pulsations are generated in the magnetosphere as ion-cyclotron waves, which propagate to the ionosphere in a longitudinal waveguide. A portion of wave energy enters the ionospheric waveguide and propagates horizontally along the Earth's surface at large distances from the end of longitudinal waveguide.

In contrast to the ionospheric duct, where the medium may be considered isotropic at least to the first approximation, the magnetospheric ducts are characterized by anisotropic medium. The ray theory of waves in such a medium is rather complex. However, there is an interesting and important case where the problem can be reduced to the familiar case of waves in isotropic medium. This is the case of quasi-longitudinal propagation of ion-cyclotron waves in the paraxial approximation (Guglielmi, 1989). The equation for the rays lying in a meridional plane can be written in the form

$$\frac{\mathrm{d}^2 x}{\mathrm{d}s^2} = -\frac{1}{2R} + \frac{1}{4N}\frac{\partial N}{\partial x} - \frac{2\Omega - \omega}{4\Omega(\Omega - \omega)}\frac{\partial \Omega}{\partial x}\,, \tag{30}$$

where $\mathrm{d}s$ is the element of the field line length, $R(s)$ is the radius of the curvature of this line, $\mathrm{d}x$ is the transversal ray shift over the route of $\mathrm{d}s$ with $\mathrm{d}x > 0$ if the ray shifts in the direction of principal normal to the magnetic field line, $N(x, s)$ and $\Omega(x, s)$ are the concentration and gyrofrequency of ions, respectively. This approach makes it possible to determine the important characteristics of propagation: the ray oscillation step along geomagnetic field line, the conditions for capture in a plasma duct and conditions for escape from a duct, etc. Without going into details, we call attention to the fact that according to Equation (30) the formation of a waveguide is possible if only the plasma density decreases abruptly with distance from the Earth, for example $N \propto L^{-12}$ in the equatorial plane if $\omega \ll \Omega$. Such a sharp drop takes place at the plasmapause and, may be, at the outer boundaries of detached plasma regions.

There are two challenging questions in the theory of Pc1 propagation in magnetospheric waveguides. Firstly, we must take into account the role of heavy ions in the magnetosphere. The ray theory is inapplicable if the wave frequency is of the order of the gyrofrequency of heavy ions. Secondly, strictly speaking, the linear approximation does not apply either, since it is supposed that pulsations are generated due to a plasma instability with a transition to a nonlinear regime.

4.3. Repetition period of pearls

The repetitive character of Pc1 wave packets or 'pearls' was noted already in the first measurements of Pc1 in 1936 (see Figure 1). Subsequently, it was reported that the individual wave packets constituting a 'pearl necklace' are detected alternately in the opposite hemispheres of the Earth (Yanagihara, 1963; Gendrin and Troitskaya, 1965). This gives us reason to suppose that a series of pearls represents a succession of echo-signals, oscillating along the geomagnetic field lines in one of the magnetospheric waveguides and reflecting from the ends of this waveguide in opposite hemispheres (Jacobs and Watanabe, 1964; Obayashi, 1965). When reflecting from the ends the signal excites the ionospheric waveguide; as a result the pearls may be observed at a distance well away from the source region (Tepley and Landshoff, 1966).

So, the basic fact of the propagation of Pc1 is the ducting of wave energy along the geomagnetic field lines with the formation of repetitive sequence of signals. At this point we start the presentation of the properties of the repetitive period τ, and firstly we consider the relation between τ and the carrier frequency f. In the following subsection we shall consider the small excursions of the wave packets from periodicity, and in Subsections 4.4, 6.1, and 6.2 we shall pursue our discussion of the other properties of τ.

There is a large body of research dedicated to the repetition period of the Pc1 'pearl' geomagnetic pulsations (Jacobs and Watanabe, 1964; Dowden and Emery, 1965; Obayashi, 1965; Pope, 1965; Watanabe, 1965; Kenney and Knaflich, 1967; Liemohn et al., 1967; Troitskaya and Guglielmi, 1967; Fraser, 1968; Feygin and Yakimenko, 1970; Offen, 1972; Dovbnya et al., 1974). However, these authors have focussed attention mainly on the fine effects of the dispersive broadening of the wave packets. The main objective of our study is to find out the relation between the repetition period and carrier frequency.

Let us derive a $\tau - f$ relation by using an extremely simplified model. The repetition period is of the order $\tau \sim l/c_{\rm A}$, where $c_{\rm A}$ is the Alfvén velocity, l is a length of the field line along which Pc1 propagates. The theory of excitation of Pc1 gives us the following estimate of a carrier frequency: $f \sim f_B(c_{\rm A}/w)$, where $f_B = \Omega/2\pi$, Ω is the gyrofrequency, w is a velocity of resonant protons. Therefore

$\tau f \sim f_B(l/w)$. It is evident that $l \sim R_E L$, where R_E is the Earth's radius. It is more difficult to obtain an estimate of w. Here we use the approximate law of the first adiabatic invariant conservation in the processes of radial drift of particle from a periphery of the magnetosphere towards the Earth. Then $w \sim V_{sw}(\Omega/\Omega_m)^{1/2}$, where Ω_m is the proton gyrofrequency at the magnetopause, V_{sw} is the solar wind velocity. Hence

$$\tau f \sim \frac{R_E}{2\pi V_{sw}}\sqrt{\frac{\Omega_E\Omega_m}{L}}\ , \tag{31}$$

where $\Omega_E = eB_E/m_i c$, $B_E \simeq 0.31$ G is the geomagnetic field intensity on the equator of the Earth.

We revealed that the product τf is expressed through the specific combination of the global parameters R_E, Ω_E, Ω_m, V_{sw}, and it depends on L. Substituting $R_E \simeq 6.4 \times 10^8$ cm, $\Omega_E \simeq 3 \times 10^3$ s^{-1}, $\Omega_m \simeq 5$ s^{-1}, $V_{sw} \simeq 5 \times 10^7$ cm s^{-1}, we obtain

$$\tau f \sim \frac{240}{\sqrt{L}}\ . \tag{32}$$

Of course, our present knowledge of excitation and propagation of Pc1 magnetic pulsations is incomplete, but the experimental facts and theoretical analysis support the view that we are dealing with ion-cyclotron waves which are generated in the vicinity of the plasmapause (see, e.g., Roth and Orr, 1975; Fraser et al., 1989; Erlandson et al., 1996). Thus L in Equation (32) is approximately equal to the McIllwain parameter of the plasmapause. If $L \simeq 4.5$ (typical value), then $\tau f \simeq 125$, in a good agreement with a lot of observations. For example, Cahill et al. (1982) have observed the Pc1 with $f \simeq 0.7$–0.8 Hz, $\tau \simeq 130$ s at observatory Siple ($L = 4$). This gives $\tau f \simeq 10^2$.

If the frequency dependence of the wave velocity is taken into account and assuming a simple plasma distribution and the dipole approximation of the Earth's magnetic field one obtains (Guglielmi, 1989)

$$\tau(x) = 8\sqrt{\pi m_0 N_0}(R_E/B_E)L^4 I(x)\ . \tag{33}$$

In this equation $I(x)$ is a function of $x = \omega/\Omega_0$. Ω_0 and N_0 are the gyrofrequency and density of protons at the top of Pc1 trajectory, respectively. If we take into account the resonance condition by Equation (10) we find

$$\tau f = \frac{2R_E\Omega_E}{\pi L^2 w_{||}}(1-x)^{3/2}I(x)\ . \tag{34}$$

If we assume the plasmasheet origin of protons (see Equation (28)) one obtains $w_{||} \propto L^{-1/2}$. In this case at $x \ll 1$, Equation (34) transforms to

$$\tau f \sim \frac{\sqrt{2}I(0)}{\pi L^{3/2}} \left(\frac{\Omega_E}{\Omega_\oplus}\right)^{1/2} , \tag{35}$$

where $I(0) = 0.67$ and $\Omega_\oplus = 7.3 \times 10^{-5}$ s^{-1} is the angular velocity of the Earth's rotation. Thus the solar wind model (Equation (32)) and the plasmasheet model (Equation (35)) lead to different relations between τ, f, and L.

It is obvious that the relation between τ, f, and L may be written in the

$$\tau f = pL^{-q} , \tag{36}$$

where p and q should be determined by simultaneous measurements of τ, f, and L. According to Equations (32) and (35) $q = 0.5$ and $q = 1.5$, respectively.

As no data is available so far let us adopt $q = 1$. Taking into account that $\tau \propto L^4\sqrt{N_0}$ (Equation (33)) and assuming $N_0 \propto L^{-4}$ (see Guglielmi, 1989) we obtain

$$\tau \propto f^{-2/3} . \tag{37}$$

Such a relation needs to be verified by experiment.

There are only a few observations of pearl pulsations by satelllites. Fraser et al. (1989) observed $\tau = 135$–160 s for $f = 0.65$ Hz at $L = 4.7$. Erlandson et al. (1996) report $\tau = 154$ s for $f = 0.6$ Hz at $L = 5.3$. These agree reasonably well with Equation (32). However, Mursula et al. (1997) show *Viking* data which make the bouncing wave packet model questionable at least for exoplasmaspheric HM chorus. They suggest a model where ULF waves modulate the Pc1 growth rate in the equatorial source region. Thus the old paradigm of more than 30 years may need to be revised.

4.4. Fluctuations of the Repetition Period

In studies of Pc1 pulsations recorded at the Finnish magnetometer network, it has been found experimentally that the repetition period τ fluctuates, with the root-mean-square deviation $\sigma_\tau = \overline{(\tau - \overline{\tau})^2}^{1/2}$ which depends on the frequency ω as well as on the average repetition period $\overline{\tau}$ (Guglielmi et al., 1996a). Accordingly, it is important to present the stochastic generalization of the theory of Pc1 propagation.

It should be taken into account that the magnetospheric plasma is an irregular medium, i.e., it contains random inhomogeneities of plasma density ρ. τ depends (via $c_{\mathrm{A}} \propto \rho^{-1/2}$) on plasma density and therefore fluctuates due to its random irregularities. Let us divide ρ into the regular density $\rho_0(l)$ and small-scale irregular fluctuations $\rho_1(l)$, and assume that $|\rho_1| \ll \rho_0$. Similarly, we write $v = v_0 + v_1$ with $\overline{v} = v_0$ and $\overline{v}_1 = 0$. The above assumption implies $|v_1| \ll v_0$, and according to Guglielmi et al. (1996a) we get

$$\sigma_\tau^2 = \frac{1}{2}\int_0^{l_0} \frac{\mathrm{d}l}{v_0^2(l)} \int_0^\infty \Gamma_\rho(\zeta)\,\mathrm{d}\zeta\;, \tag{38}$$

where $\Gamma_\rho(l', l'') = \rho_0^{-2}\overline{\rho_1(l')\rho_1(l'')}$ is the correlation function of the density fluctuations, $\Gamma_\rho(l', l'') = \Gamma_\rho(l' - l'')$. We ignore here the possible correlation of fluctuations on the back and forth segments of Pc1 trajectory between conjugate points. Had we taken this correlation into account, the right-hand part of Equation (38) should be multiplied by $\sqrt{2}$ (see below). In the case of a dipole field we have

$$\sigma_\tau = \sigma_\rho c_{\mathrm{A}}^{-1}[2l_\rho R_\oplus J(\omega)]^{1/2}[L(L-1)]^{1/4}\;. \tag{39}$$

Here $\sigma_\rho^2 = [\Gamma_\rho(0)]$ is the dispersion and

$$l_\rho = \frac{1}{\sigma_\rho^2}\int_0^\infty \Gamma_\rho(\zeta)\,\mathrm{d}\zeta$$

is the correlation length of plasma density fluctuations, and

$$J(\omega) = \frac{1}{x_0}\int_0^{x_0} \frac{[2-\omega/\Omega(x)]^2(1-x^2)^{6-s}}{[1-\omega/\Omega(x)]^3(1+3x^2)^{1/2}}\mathrm{d}x\;,$$

where

$$\Omega(x) = \Omega_0(1+3x^2)^{1/2}/(1-x^2)^3\;, \quad x_0 = (1-1/L)^{1/2}\;.$$

Plasma distribution along the Pc1 trajectory can be modelled by $\rho_0(x) = \rho_0(0)(1-x^2)^{-s}$.

After these considerations Guglielmi et al. (1996a) obtained the relation between the root-mean-square deviation σ_τ and the mean repetition period $\overline{\tau}$

$$\sigma_\tau = C\sigma_\rho(l_\rho/R_\oplus L)^{1/2}\overline{\tau}\;. \tag{40}$$

The proportionality factor $C = (x_0 J/8)^{1/2}/I$ is fairly constant (about 0.4) for relevant L and ω values. Therefore, Equation (40) expresses a nearly constant linear relation between σ_τ and $\overline{\tau}$ with σ_ρ, $l_\rho^{1/2}$ and trivial scaling factors as coefficients. The observations support the theory with $\sigma_\rho/\overline{\tau} \sim 0.1$ as a typical value. This corresponds to the dimensionless parameter $\sigma_\rho(l_\rho/R_\oplus L)^{1/2} \sim 0.25$ which is a characteristic of 'cloudiness' of the magnetosphere in the region of Pc1 propagation.

We come back to our previous remark about the correlation of plasma density fluctuations and the back and forth segments of Pc1 trajectory. Analyzing the reflection of radio-waves from the ionosphere, Denisov and Erukhimov (1966) have discovered theoretically an enhancement of wave field fluctuations associated with the coincidence of the phases of waves travelling in opposite directions. By analogy, we would expect that the same effect exists in the series of Pc1 pearls. If so, σ_τ is replaced by $\sqrt{2}\sigma_\tau$. In other words, the deviation increases by a factor of $\sqrt{2}$ as compared with the case of missing correlation on the back and forth segments of the path. However, which of these alternatives takes place in reality?

Let us compare $\sigma_{2\tau}$ and σ_τ to find an answer to this question. If correlation is present and the Denisov–Erukhimov effect exists in the Pc1 series then $\sigma_{2\tau} = 2\sigma_\tau$; if the correlation is absent then the classical relation $\sigma_{2\tau} = \sqrt{2}\sigma_\tau$ should be valid. The third alternative $\sigma_{2\tau} = \sigma_\tau$ corresponds to the case when the fluctuations of τ are artificial, i.e., they are due to measurement errors only. According to our data $\sigma_{2\tau}/\sigma_\tau = 1.4 \pm 0.1$ which means that the second alternative seems probable. This phenomenon may be related to temporal fluctuations of the plasma density with the correlation interval less than 2τ. Another possible explanation is based on the idea of many-path propagation of Pc1. The first alternative cannot be excluded completely. This is due to the difficulties in determining the measurement error.

5. Regular Variations of Pulsation Activity

In the earlier sections we were dealing with the transient variations of the pulsation activity. In this section we shall consider the periodic variations, namely the daily, seasonal, 27-d and 11-yr variations. This allows us to supplement substantially the pulsation morphology, and also to have a new view on the physical problems of pulsations.

5.1. Earth's Rotation

The geomagnetic dipole axis is tilted eleven degrees about the axis of the Earth rotation. This leads to a permanent modulation of magnetospheric processes with the modulation periods equal to the terrestrial rotation period and its harmonics, because the spatial distribution of geomagnetic field depends on the angle between the dipole axis and the solar wind direction. The global daily modulation of this kind is said to be unitary or UT variation. The study of UT variation of the pulsation activity is of obvious physical interest; however, we do not go into any details of this topic.

Another manifestation of the Earth's rotation, namely, the local time dependence of the pulsation activity has been much studied. This dependence is due to a severe asymmetry of the magnetosphere and ionosphere in relation to the Earth's rotation axis resulting in a daily modulation of the pulsation parameters at a given point of observation. Table II outlines a general idea about the most probable occurrence of the short-period pulsations during a day. Brief mention has already been made of this dependence above. Now, we shall consider the daily variations

Table II
LT dependence of the pulsation activity

Pc1	Noon at high latitudes
	Dawn at low latitudes
Pc2	Noon
PiB	Midnight
PiC	Dawn
Ipdp	Dusk

of the pulsation activity in more detail based on the results of the fundamental investigations which have been accomplished by Troitskaya (1961, 1964), Heacock and Hessler (1962), Campbell (1967), Kenney and Knaflich (1967), Fraser (1968), Fukunishi (1969), Saito (1969), Fraser-Smith (1970, 1982), Kangas et al. (1974, 1976), Horita et al. (1979), Fukunishi and Toya (1981), Fukunishi et al. (1981), Pikkarainen (1987, 1989), Morris and Cole (1991), Mursula et al. (1994b, 1996), Erlandson and Anderson (1996).

At the middle latitude station, Uzur near Irkutsk ($\Phi = 41°$, $L = 1.76$), the daily variation of the Pc1 occurrence has the form of a twofold wave with the main maximum early in the morning (4–6 LT) and a minimum in the evening (16–19 LT), and additional maximum and minimum in the midday (12–13 LT) and in the morning (8–9 LT), respectively (Vinogradova, 1969). The mean frequency is equal to $\sim$ 1 Hz in the morning, and $\sim$ 0.5 Hz at noon. The probability to observe the Pc1 early in the morning is bigger than in the evening by a factor of 3.

The observations of daily variations at the higher latitude station (Borok, $\Phi = 53.6°$, $L = 2.8$) had given an insight into the difference between the groups of Pc1 pulsations with periods $T \leq 2$ s and $T > 2$ s (Troitskaya, 1964; Matveyeva, 1969). Both groups show a pronounced dependence on solar activity (see below in Subsection 5.3). But the overall picture of daily variation of pulsations with $T \leq 2$ s looks the same in the minimum and in the maximum of solar cycle, and it has a broad maximum of Pc1 occurrence in the morning hours. On the other hand, for the pulsations with $T > 2$ s there is no clear daily variation in the years of solar maximum, whereas in the years of solar minimum there exists a pronounced daily variation with a sharp peak of the Pc1 occurrence at noon. There must be a specific physical reason for this difference between the two groups of Pc1. Since the limiting period $T = 2$ corresponds to the mean cutoff frequency of the ionospheric waveguide ($f_c \sim 0.5$ Hz), then it is reasonable to suggest that the difference in daily variations is due to dissimilar conditions for the horizontal propagation of waves. Kenney and Knaflich (1967) presented the diurnal variation of the midfrequency of Pc1 at Tulalip near Seattle ($\Phi = 53.6°$, $L = 2.81$), which can be described by a 24-hr harmonic curve with the maximum in early morning and the minimum in afternoon. This may reflect the corresponding diurnal variation of the cutoff frequency. An alternative interpretation can be suggested: the midfrequency depends on the local time due to diurnal variation in L value of magnetospheric sources of Pc1 (Fraser, 1968; Lewis et al., 1977).

At Eights Station in Antarctica ($\Phi = 63.8^\circ$, $L = 3.88$) the occurrence rate of Pc1 events with frequency of the order of 1 Hz as a function of local time has a broad peak in the 04–10 LT sector, what is somewhat later than in middle latitudes (Campbell, 1967). The similar shift of the occurrence to the later local time takes place at Sodankylä ($\Phi = 63.8^\circ$, $L = 5.1$) for the structured Pc1 waves (Mursula et al., 1994b). The diurnal distribution of the unstructured Pc1 observed at Sodankylä has a clear peak near noon. At the same time, the diurnal variation of midfrequency at high latitudes is very similar to that at the midlatitudes, i.e., the highest frequencies is observed in the early morning hours, while the lowest one being observed around noon (Campbell, 1967; Lanzerotti, 1978; Hayakawa et al., 1992b).

In summary, the overall picture of the diurnal variation of Pc1 pulsations is characterized by a systematic shift of the main peak of occurrence from morning to noon when moving from the middle to high latitudes, and also by the systematic lowering of midfrequency at this main peak.

In contrast to Pc1, the diurnal variation of Pc2 pulsations is still only poorly investigated. Much remains to be learned about the morphology of Pc2 . It is questionable if the Pc2 is a night phenomenon as was described by Jacobs (1964). At middle latitudes at high geomagnetic activity ($Kp > 3$) these pulsations are more likely to be observed at noon than at night. For example, at Boulder ($\Phi = 48.9^\circ$) the daily variation of pulsations with periods near 12 s has the early afternoon maximum and dawn minimum (Wertz and Campbell, 1976). The diurnal variations in Pc1-2 occurrence and amplitude at the Antarctic station Davis ($\Phi = 76.8^\circ$) show clear maxima near solar noon (Morris and Cole, 1991). On the other hand, Neudegg et al. (1993) revealed the presence of an additional maximum near magnetic midnight, which indicates that UT variation of the pulsation activity exists, and it may be detected by using relatively simple techniques.

The two subgroups of irregular pulsations Pil, namely PiB and PiC, are considerably distinct from each other by their diurnal variation (Heacock, 1971). It has been confirmed by many works that the maximum of occurrence of PiB falls in the midnight sector, whereas PiC is usually observed in the 02–04 LT interval, i.e., before the dawn (e.g., Gendrin, 1970).

Ipdp's are typically a dusk phenomenon but in fact they may be observed over quite an extended local time sector. Most Ipdp events occur in the 15–21 LT interval. According to Pikkarainen (1989) the mean onset time of Ipdp at the Finnish meridian is 17:20 LT at auroral latitudes. At lower latitudes this time is somewhat later. With increasing of geomagnetic activity, the distribution of Ipdp's is displaced toward earlier local times and lower latitudes. The distribution of the frequency-time plots of Ipdp recorded at Oulu in 1974–1975 is shown in Figure 19. We can see that the events can be divided into three groups according to their local

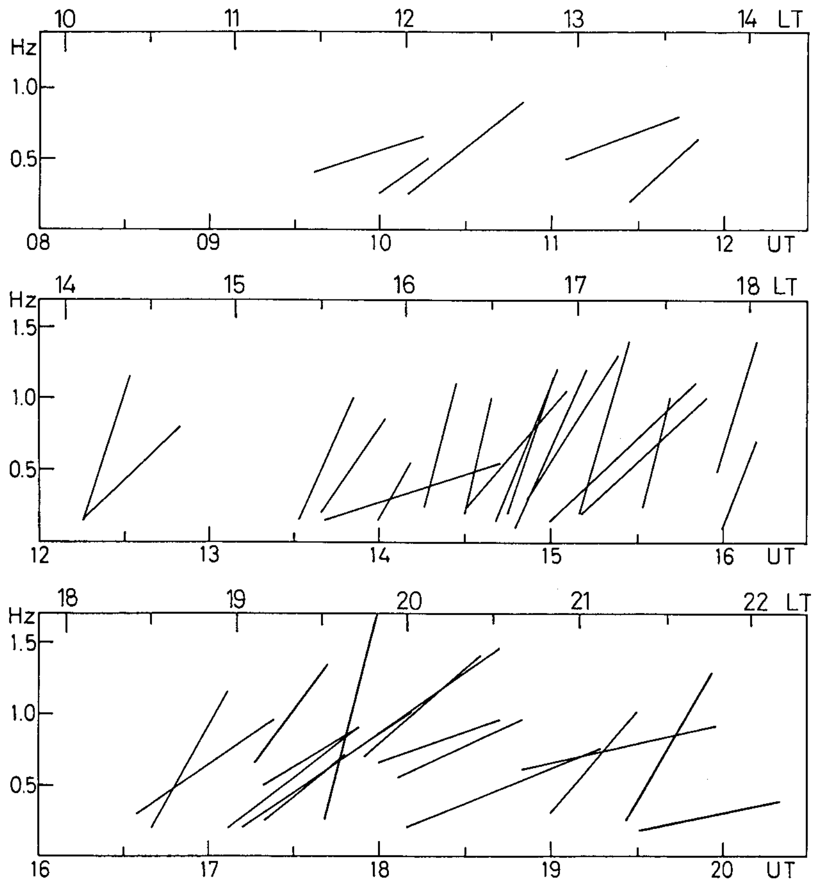

Figure 19. Frequency-time plots of IPDP's observed at Oulu, in 1974–1975. Events are divided into three groups according to their local time occurrence (after Pikkarainen et al., 1983).

time occurrence. The events are rare in the local noon and near midnight sectors. It is notable that the slope of many Ipdp's in the dusk sector is rather steep.

Fukunishi and Toya (1981) discovered a very peculiar type of the pulsations with rising frequency which is called 'morning Ipdp'. These pulsations appear in the morning hours. The morning Ipdp is characterized by a number of uncommon properties. For example, midfrequency rises almost linearly over the entire duration of event; the frequency-time plot consists of irregularly spaced elements with very narrow bandwidth, etc. No explanation for these peculiarities exists at present.

Many interesting and unusual kinds of short-period pulsations have been registered in the polar cusp and cap. Signals of falling tone, so-called serpentine emissions and usual Ipdp's at the geomagnetic poles have been reported. The observation of Ipdp is especially interesting since it cannot be described in the frame of the energy dispersion theory of Ipdp. For further reading on these short-period pulsations we recommend the reviews by Lanzerotti (1978) and Fraser-Smith (1982).

In closing this subsection, we shall take a quick look at satellite investigation of the diurnal distribution of pulsations. Note, that the occurrence probability of Pc1 at a satellite is usually lower than on the ground. For example, the ratio of Sodankylä Pc1 events not seen on AMPTE/CCE satellite over those seen by AMPTE/CCE is 1.25 (1.5) for the low (high) sunspot time (Mursula et al., 1996). In both low and high sunspot times, the Pc1 occurrence has its diurnal maximum in the postnoon hours. The majority of events were recorded by AMPTE/CCE at $L > 7$, and it was observed that the average normalized frequency ω/Ω_{H+} decreases with local time (Anderson, 1996).

Most Pc1 activity was detected by the *Freja* double probe sensor at the ionospheric altitudes within a small latitudinal range, extending from 60° to 63° CGMlat (Mursula et al., 1994c). At the same time, the local time range of Pc1 events was 03–14 MLT, with a clear dawn-dusk asymmetry and with maximum of occurrence of pulsations in the morning sector of the magnetosphere.

A total of 390 Pc1 wave events at frequencies between 0.4 and 2.0 Hz was detected by the Dynamic Explorer satellite (Erlandson and Anderson, 1996). Most events were observed in the dawn (04–06 MLT) and noon (10–15 MLT) sectors from 50° to 62° INV at ionospheric altitudes.

5.2. Earth's orbital motion, and Sun's rotation

The Earth's axis is tipped to the plane of its orbit, which manifests itself in the seasonal variation of the activity of pulsations. There are three evident causes of such a variation. First, the mean angle between the solar wind and geomagnetic axis varies with the season. Further, differences in the ionospheric conditions in northern and southern hemispheres vary by season. Finally, local ionospheric conditions at a given point of observation change with the season. In addition to these causes the heliolatitude of the Earth, as well as the distance to the Sun are changing in the course of orbital motion.

The Sun's rotation also exerts control over the geomagnetic pulsations. The 27 d quasi-periodicity in the pulsation regime is due to the axial asymmetry of the Sun, which is manifested by long-lived active heliolongitudes, sector structure of interplanetary magnetic field, etc. The patterns of seasonal and 27 d variations are superimposed, and it is not easy to separate them.

The consensus at present is that Pc1 pulsations are most often observed in winter, and they are rare in summer. This is to be expected when it is remembered that the ionospheric attenuation of Pc1 waves, as a function of season, has a maximum (minimum) in summer (winter). However, a closer look makes the interpretation of experimental data more difficult. Indeed, in reality the winter maximum of occurrence is observed for the structured Pc1 with the frequencies $>$0.5 Hz in the middle latitudes. If any of these three conditions breaks down, the pattern becomes unclear. For example, unstructured Pc1's of the type 'hydromagnetic hiss' are more frequent in summer than in winter (Tepley and Amundsen, 1965). According to Troitskaya (1964) and Matveyeva (1969), the Pc1 with periods of $T > 2$ s has minimum occurrence in winter. Moreover, in the polar caps the structured Pc1 pulsations occur most often during the summer months, when the polar regions are in continuous daylight (see Fraser-Smith, 1982). On the other hand, Morris and Cole (1991) observed the winter peak in the Pc1-2 occurrence at Davis, Antarctic. It is evident that additional investigations are still needed in this field.

The first direct experimental evidence for the presence of modulation of the Pc1 activity with the period of Sun's rotation was presented by Troitskaya et al. (1972). Up to then, the search for a 27-d recurrence of Pc1 activity was for a long time unsuccessful.

Higher than usual appearance of Pc1 at the sector boundaries (McPherron and Ward, 1967) suggests that a specific combination of the solar wind parameters is favorable to self-excitation of ion-cyclotron waves in the magnetosphere. Matveyeva et al. (1972b) have discovered that the appearance of Pc1 with $T \leq 2$ s is most probable when the interplanetary plasma density is high ($N \geq 30$ cm^{-3}), solar wind velocity is low ($V \leq 250$ km s^{-1}), and the modulus of z-component of the interplanetary magnetic field is high enough ($|B_z| \approx$ 3–5 nT). Sobolev (1986) has confirmed only the plasma density dependence but not the others.

The influence of the Earth's orbital motion and Sun's rotation on the activity of other short-period pulsations has not been sufficiently explored. The 27-d periodicity is found in variations of all kinds of pulsations; however, further detailed studies are needed into the relations of pulsation regimes with the sector structure of the interplanetary magnetic field, with the active heliolongitudes, etc. There is a need for some further morphological analysis of these relations. As to the seasonal variation, the peaks of activity of the PiB, PiC, and Ipdp pulsations are observed at the equinoxes; no clear explanation of these measurements has been made.

5.3. Solar cycle

The Sun is a variable star. The most pronounced variation of solar activity with a quasi-period of 11 years is called the solar cycle. One of the manifestations of the solar cycle is the 11-year periodicity of geomagnetic pulsations, which has been studied by several authors. The results of such studies can shed light on the problems of excitation and propagation of ion cyclotron waves in the magnetosphere and ionosphere. They may also have some practical applications, for example, in the planning of observation programs, in magnetotelluric studies, etc. (Fraser-Smith, 1970).

Benioff (1960) was most probably the first who called attention to the inverse relation of the Pc1 occurrence with sunspot cycle. He and Troitskaya (1964), Matveyeva (1969, 1987), Fraser-Smith (1970, 1981), Matveyeva et al. (1972a), Lee and Fraser-Smith (1975), Strestik (1981), Kawamura et al. (1983), and Fujita and Owada (1986) explored the problem using the observations of Pc1 both at low and mid-latitudes. The systematic investigation of pulsations at high latitudes was performed by Mursula et al. (1991, 1994b, 1996). The general conclusion is that the dominant feature of the long-term behavior of the Pc1 activity is the 11-year solar activity cycle, and that more Pc1 pulsations occur during sunspot minimum years than during the maximum years. Let us consider this point in greater detail.

Figure 20 shows the distribution of Pc1 activity at Sodankylä together with the annual averaged sunspot numbers. In spite of some statistical variations the dominant feature over the whole registration time is the quasi-periodic appearance of years of high and low number of Pc1 events. The length of the pulsation activity cycle seems to be very close to the length of the solar activity cycle. Moreover, the most active Pc1 years fairly closely coincide with lowest sunspot years and *vice versa*, thus showing a strong negative correlation between the two variables over the whole data period (Mursula et al., 1991).

It is interesting to compare the solar cycle behavior of the two dominant types of Pc1 observed at high latitudes, namely, the structured and unstructured pulsations. Mursula et al. (1994b) observed altogether 677 events at Sodankylä during the 8 months covering the two spring equinox months in two sunspot minimum years, 1975–1976, and in two maximum years, 1979–1980, with a total Pc1 active time of more than 42 days. The average length of all Pc1 events was about 90 min. The results of the analysis are given in Table III. First of all, one can see that there is a strong reduction in overall Pc1 activity from the low sunspot years to high activity years. Secondly, we can see that the structured (unstructured) Pc1's were reduced by the factor of about 10 (7). It is also interesting to note that the relative fraction of unstructured pulsations remained constant over the sunspot cycle so that 53% of all Pc1 both in minimum and maximum years were classified as unstructured pulsations. On the other hand, the relative fraction of structured pulsations in maximum years (30%) was smaller than in minimum years (40%). This reduction is seen as an increase in the relative amount of the other types of Pc1's during maximum years. Finally, in sunspot maximum years, the average duration of structured pulsations remains approximately the same as in minimum years but the unstructured pulsations get shorter by a factor of 2, being thus approximately as short as the remaining events whose average duration remains the same over the sunspot cycle.

Table III shows also that the average frequency of structured pulsations is higher than that of unstructured pulsations. In sunspot minimum years this difference was as large as 0.32–0.33 Hz. In sunspot maximum years the average frequencies of all pulsations were at least a little lower than the corresponding values in minimum years. This decrease was particularly large for structured pulsations.

The diurnal distribution of unstructured pulsations in minimum years is an almost Gaussian form around the maximum at 13 LT (see also Subsection 5.1). Its nighttime activity is more than an order of magnitude lower than in daytime. On the other hand, the distribution of structured Pc1's in minimum years has a far less

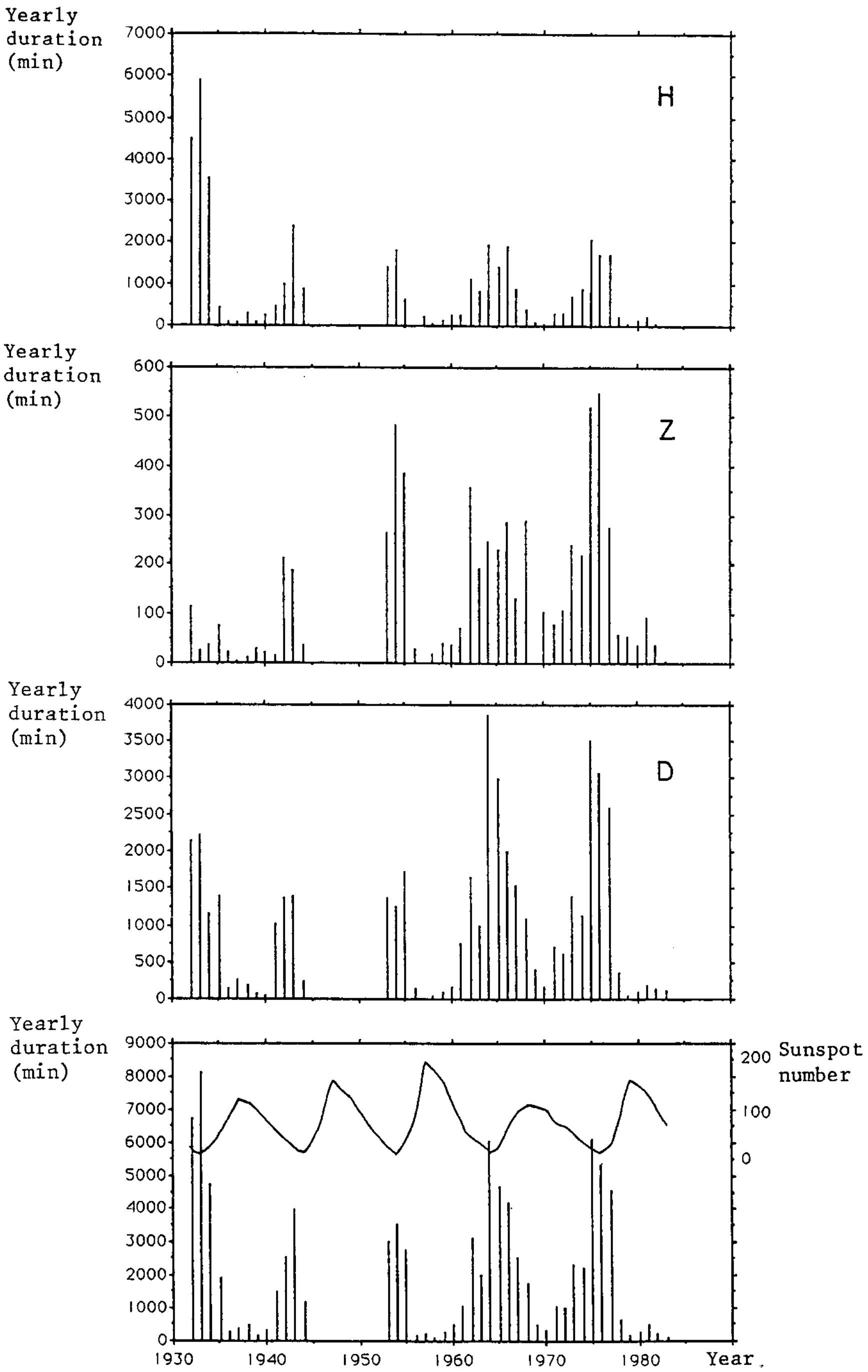

Figure 20. The annual sums of durations (in minutes) of the quick-run Pc1 pulsations in H component (top), Z component (second), D component (third) and all three components summed (bottom) in Sodankylä since 1930's. The averaged annual unsmoothed sunspot number (solid line) is also shown at the top of the bottom figure with the scale on the right-hand side (after Mursula et al., 1991).

Table III

Number of events, total times (minutes/relative percentages) and average frequencies (Hz) of structured, unstructured and other Pc1 pulsations during sunspot minimum years (1975–1976) and maximum years (1979-1980). (From Mursula et al., 1994)

	Number of events	Total time (min/%)	Average frequency (Hz) according to max. intensity	band average
1975–1976				
Structured	214	20975/40	0.75	0.77
Unstructured	266	28187/53	0.43	0.44
Other	72	3928/7	0.75	0.78
All	552	53090	0.58	0.60
1979–1980				
Structured	21	2219/30	0.63	0.64
Unstructured	79	3936/53	0.38	0.40
Other	25	1292/17	0.70	0.69
All	125	7447	0.51	0.52

pronounced maximum in late morning hours. Its activity remained relatively high through the day and night, exceeding that of unstructured pulsations outside the noon–afternoon sector.

In sunspot maximum years, the pronounced postnoon maximum of the unstructured pulsations also exists but seems to be shifted by 1–2 hours later. The diurnal distribution of structured Pc1's in maximum years was also slightly different from that in minimum years: the events almost exclusively appeared during morning hours (Mursula et al., 1994b).

The solar cycle variation of short-period pulsations other than Pc1 is less understood. The behavior of Pc2 is characterized by the maximum occurrence rate and minimum of the carrier frequency in the epoch of solar maximum (e.g., Troitskaya and Guglielmi, 1967). Wertz and Campbell (1976) discovered that there is a positive correlation between the pulsations with periods near 12 s at College and sunspot numbers. Correlation coefficient between the sunspot number and daily average Pc2 intensity equals $r = 0.62$ for monthly means, and $r = 0.82$ for annual means. The amplitude of pulsations varies from $\sim$ 10 nT at sunspot number $R_z = 10$ up to $\sim$ 40 nT at $R_z = 100$. It is interesting to compare the correlation of the Pc2 activity with the indexes AE ($r = 0.7$), and Dst ($r = 0.16$).

We describe now the properties of Ipdp in the course of solar cycle, following Pikkarainen (1987) and Maltseva et al. (1988). The Ipdp events recorded on the ground are more numerous in the years of low solar activity than during elevated solar activity. In Figure 21 we show the number of events at Sodankylä in the years 1974–1993 together with the mean sunspot number R_z. It is interesting and important to note a great similarity between Ipdp and Pc1 solar cycle variations (see Figure 20 for comparison).

The search for any long-term variation in other Ipdp characteristics leads to the following conclusions. The highest end frequency in the interval of pulsations has been $\sim$ 0.8 Hz or smaller at all Finnish stations in the solar active years whereas in quiet years it is above $\sim$ 1.2 Hz as a rule. The frequency modulation slope $\mathrm{d}f/\mathrm{d}t$ is also smaller in active years than in quiet ones although the variability of this slope is great: 0.3–1.2 Hz hr^{-1} and 0.8–1.7 Hz yr^{-1}, respectively.

The most remarkable result of the study presented in this subsection is the inverse relation between the Pc1 as well as Ipdp occurrence and solar activity. No accepted theory of this phenomenon has been postulated. In this situation, it is important to find the physical parameters which govern the long-term variation of the pulsation activity. We can identify three parameters, which seem to be important: (a) absorption in the ionospheric MHD waveguide, (b) the density of O^+ ions in the magnetosphere, and (c) plasma density of the solar wind. The two first parameters become less significant in solar mimumum years whereas (c) is enhanced in such conditions. For the discussion of possibilities (a), (b), and (c) see the papers by Pikkarainen (1987), Mursula et al. (1994b, 1996), and Sobolev (1986), respectively.

6. Physical and Geophysical Applications

The results described in previous sections were obtained by using the known physical and geophysical models. On other hand, as it will be shown below, the measurements of pulsations are most useful for the solution of some geophysical problems. In addition, the difficulties in understanding of the origin of pulsations have given an impetus to the development of the physics of the nonlinear waves.

6.1. MTS AND HMD

The essence of magnetotelluric sounding (MTS) lies in the evaluation of the vertical distribution of the conductivity of the Earth's crust by the frequency dependence of the surface impedance which is found from the observations of geoelectromagnetic waves. On the other hand, the hydromagnetic diagnostics (HMD) is a method which gives information for drawing conclusions about the state of the magnetosphere on the basis of observations of the same waves. Both of these applications have been adequately elucidated in the literature, as to the MTS see, e.g., Wait (1982) and Berdichevsky and Zhdanov (1984). HMD has been described by Troitskaya and Guglielmi (1967), Aubry (1970), Guglielmi (1974), and Nishida (1978). Chetaev (1970) and Guglielmi (1989) presented the idea of a similarity between these two methods. Here we shall discuss shortly some of the MTS and HMD problems.

The impedance relations on the ground have the form

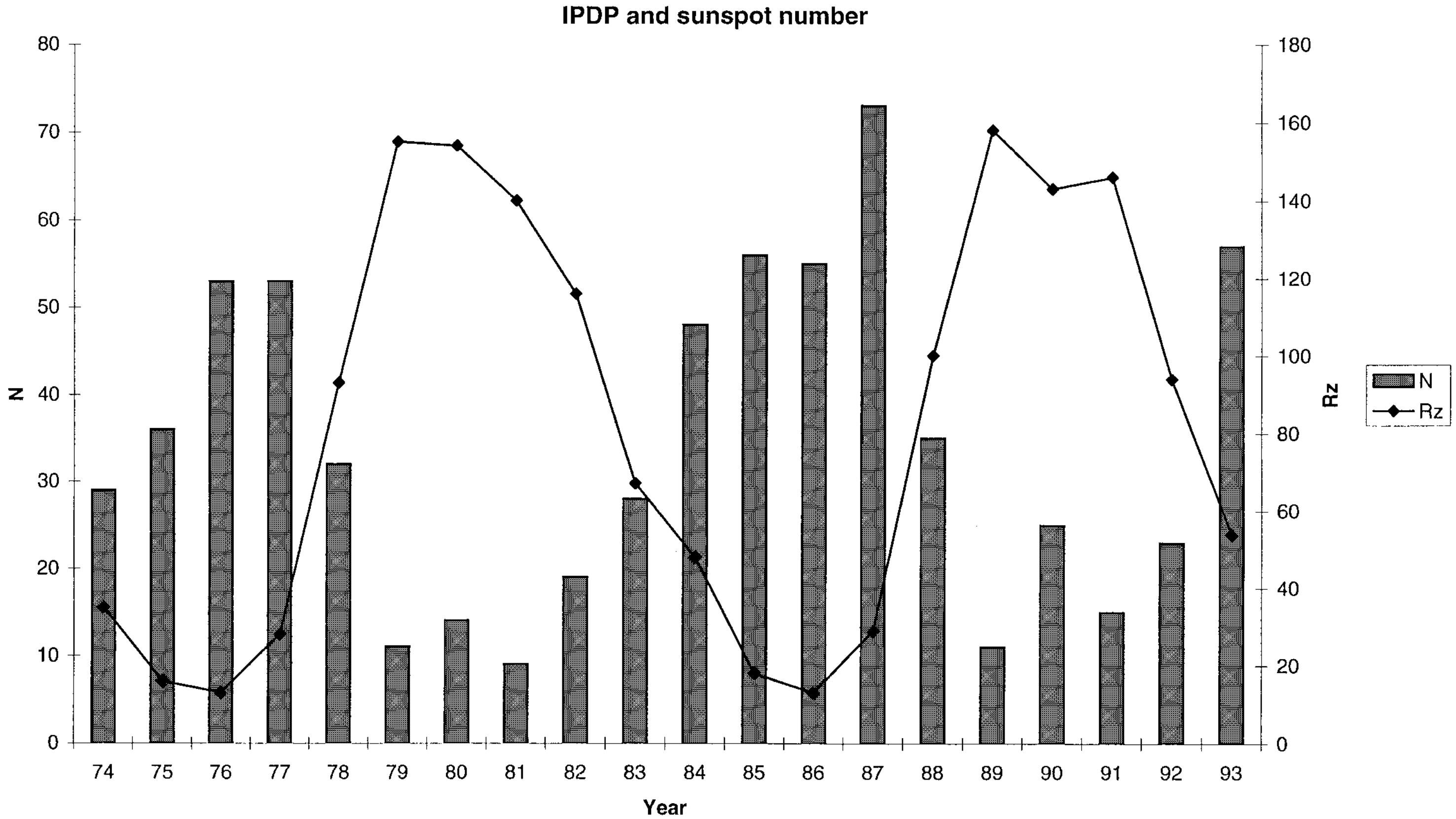

Figure 21. Annual rate of the IPDP occurrence in Sodankylä in 1974–1993. Annual mean of the sunspot number R_z is given by the solid line. (Extension of the data presented by Maltseva et al., 1988).

$$E_x = \zeta b_y \ , \quad E_y = -\zeta b_x \ , \tag{41}$$

where ζ is the surface impedance of the Earth. Here $E_{x(y)}$ is the north–south (east–west) component of the electric field, and similarly $b_{x(y)}$ for the magnetic field. Substituting (41) into the induction equation, we get

$$b_z = i\lambda\nabla \cdot (\zeta \mathbf{b}_t) \ , \tag{42}$$

where $\lambda = c/\omega$, $\mathbf{b}_t = (b_x, b_y)$. Let us consider the situation when $l_\zeta \ll l_b$, where l_ζ and l_b are the scale lengths of the horizontal variation in the impedance and horizontal projection of the magnetic field, respectively. This situation is typical for the Pc1 propagating in the ionospheric waveguide. For example, at the frequency $f = 1$ Hz the horizontal wavelength in the ionospheric waveguide is approximately 500 km (see Subsection 4.4). This value is much more than the typical scale of horizontal inhomogeneity of the crust. Then the simplified formula

$$b_z = i\lambda(\mathbf{b}_t \cdot \nabla\zeta) \tag{43}$$

follows from Equation (42). Therefore, by using the relations (41) and (43), we are able to extract information not only on the impedance ζ, but the surface gradient $\nabla\zeta$ as well, from the measurement of two electric and three magnetic components at a single point.

In general, it is not possible to avoid the procedure of multipoints measurements. It is interesting and useful to know, that in these cases one can restrict the measurements only in magnetic components at each point (Guglielmi, 1989). Let us rewrite Equation (42) in the form

$$A\frac{\partial\zeta}{\partial x} + B\frac{\partial\zeta}{\partial y} = C\zeta = D \ . \tag{44}$$

We shall consider Equation (44) to be a differential equation in order to find the impedance $\zeta(\omega; x, y)$ at a fixed frequency ω under the condition that the coefficients $A = b_x$, $B = b_y$, $C = \nabla \cdot \mathbf{b}_t$, $D = b_z/(i\lambda)$ are known from observations. Many authors have used previously the algebraic relation $\zeta = D/C$ (e.g., Pajunpää, 1988). The impedance equation (44) represents a useful generalization to the horizontally inhomogeneous Earth's crust.

For the purposes of the HMD, let us consider the relation (42) once more. If ζ is independent of x, y, then $b_z = i\lambda\zeta\nabla \cdot \mathbf{b}_t$. Setting $b_z = 0$, we obtain $\nabla \cdot \mathbf{b}_t = 0$. For the Pc1 in the ionospheric waveguide the operator ∇ may be replaced with $i\mathbf{k}$, where $\mathbf{k} = (k_x, k_y)$ is the local wave vector of horizontal propagation. Hence $\mathbf{b}_t \cdot \mathbf{k} = 0$, i.e., vector $\mathbf{b}_t$ is parallel with the wave front, and it is perpendicular to the direction of propagation when $b_z = 0$.

The horizontal projection of the magnetic field rotates because of the quasi-elliptic polarization of Pc1 waves. It indicates the direction of Pc1 propagation twice over the period of oscillations, much as a stopped clock shows the right time twice a day. Referring to the above the rotating line coincides with the propagation direction when $b_z(t) = 0$. Hence, we have a technique for the measurement of the azimuth of the Pc1 propagation. If needed, we can take into account a weak dependence of ζ on x, y (see Guglielmi et al., 1997). All one has to do is to replace b_z by $b_z - i\lambda \mathbf{b}_\tau \cdot \nabla\zeta$. The realization of this version requires preliminary investigation of the geoelectric structure of the region in the vicinity of the observation point. The position of the Pc1 source region may be estimated, in principle, by the direction finding of Pc1 at two or more points.

The information on the source position of Pc1 is very important in HMD applications (e.g., Nishida, 1978). The problem of location can be solved, e.g., by the triangulation direction of arrival method (Frazer and Wawrzyniak, 1978), or by directional analysis method (Chetaev, 1970) or by the dispersion and group delay method (see Feygin et al., 1979, and references therein).

Mention will be made shortly of an additional method which allows us to estimate the L-position of the Pc1 source. The technique is based on the relation (22). It may be rewritten in the form

$$L \approx a_i(\Delta f/Af)^{1/3} ,$$

with $a_1 \approx$ 20.6, or $a_2 \approx$ 25.9 depending on the fact if the remark at the end of Subsection 2.4 should be taken into account or not. The typical value $\Delta f/Af \sim 10^{-2}$ nT^{-1} leads to the estimations $L_1 \sim$ 4.4, or $L_2 \sim$ 5.6. With the knowledge of L, f, and τ, it is possible to estimate the plasma density at the top of Pc1 trajectory by the usual methods (e.g., Troitskaya and Guglielmi, 1967).

As is clear from Subsection 4.2, the dimensionless parameter $\tau\omega$ is of particular importance for the HMD. Here we present how this parameter can be used as a tool for estimation of the large-scale electric field in the magnetosphere. Using relation (27), let us rewrite Equation (35) as

$$E \approx (\tau\omega)^{4/3} E_\oplus , \tag{45}$$

where

$$E_\oplus = \left(\frac{m^2 \Omega_\oplus^5 M_\oplus}{e^2 c} \right)^{1/3} ,$$

In this formula $\Omega_\oplus$ is the Earth's angular velocity and $M_\oplus$ is the magnetic moment of the Earth which leads to a value $E_\oplus = 1.2 \times 10^{-4}$ mV m^{-1}. For a value $\tau\omega \sim 600$ we obtain $E \sim 0.6$ mV m^{-1}, as might be expected in a typical situation.

To give a more specific case we analyze the pulsation event observed on 15 December, 1984 (see Figure 18). As we see, the transition of the pulsation regime from the classical ‘pearl necklace’ to an Ipdp-like regime is accompanied by the steady increase of τf. Before and after PiB (the vertical line at ~20:30 UT) we observe $\tau f \approx 65$ and $\tau f \approx 105$, respectively. This corresponds to an increase in electric field from $E \approx 0.3$ mV m^{-1} to $E \approx 0.7$ mV m^{-1} if (45) is adopted. Note, that E has increased already long before the PiB which signifies the onset of the substorm.

We have a possibility to check the above theory in the following way. The theory gives us the relation

$$\Delta E/E = \nu(\Delta\omega/\omega)\ , \quad \nu \approx \tfrac{4}{7} \approx 0.57\ . \tag{46}$$

This follows from Equations (15), (28), and (45). The parameter

$$\Lambda = \frac{\mathrm{d}\ln\tau/\mathrm{d}t}{\mathrm{d}\ln f/\mathrm{d}t}$$

is a measure of the combined variation of $\tau(t)$ and $f(t)$. An important point is that Λ can be estimated theoretically, and it is obtained also from ground-based observations. By using Equation (45) we obtain

$$\Delta E/E = (1+\Lambda)(4\Delta\omega/3\omega)\ . \tag{47}$$

In order to estimate the true values of Λ, Guglielmi et al. (1996b) analyzed data of Pc1 observations from the Finnish magnetometer network. They found the distribution of the events with the maximum at $\Lambda \approx -0.6$. Substituting this in the relation (47), we obtain the empirical value $\nu \approx 0.53$ in a rather good agreement with the theoretical estimation $\nu \approx 0.57$.

The technique presented above may be used as an adjunct to other diagnostic methods for the evaluation of information about the slow variations of the large-scale electric field in the magnetosphere.

6.2. Modification of Medium under the Action of Short-Period Pulsations

The short-period pulsations can act back on the magnetosphere and ionosphere in a variety of ways. We have already referred to this feature in Subsection 4.1. Pitch-angle redistribution and the leakage of energetic particles from the radiation belt are familiar manifestations of the pulsation impact on the plasma environment. Now, we shall consider another manifestation, namely, the ponderomotive redistribution of the background plasma under the action of short-period pulsations (Lundin and Hultqvist, 1989; Guglielmi, 1992; Guglielmi et al., 1996b). We treat this problem in the frame of a simple model of diffusion equilibrium by taking into consideration the multicomponent composition of magnetospheric plasma in the calculation of ponderomotive forces. Note that the influence of long-period pulsations on the spatial distribution of plasma was considered by Allan (1992), Allan and Manuel (1996).

We begin with the redistribution of magnetospheric ions along the geomagnetic field lines under the action of Alfvén waves ($\omega \ll \Omega$). The equation of the balance of forces has the form

$$T \partial \ln N_i / \partial s = \left(m_i - \frac{m_+}{2} \right) G \; . \tag{48}$$

Here $m_+ = \rho / N$ is the mean ion mass, $N = \Sigma N_i$ is the total concentration of ions; the index $i = 1, 2, \ldots$ labels the kinds of ions, ∂ is the spatial derivative along a field line of $\mathbf{B}$. For simplicity we assume that each ion has a single charge, and plasma as a whole is isothermal ($T_e = T_i = T$). Equation (48) differs from the usual one in only one respect: the longitudinal projection of gravitational acceleration $g_{||}$ is replaced by $G = g_{||} + a$, where the ponderomotive acceleration equals

$$a = -(b^2 / 8\mu_0 \rho) \partial \ln \rho / \partial s \; . \tag{49}$$

Here b is the amplitude of the travelling Alfvén wave. We can see that a is independent of B and it is directed toward decreasing ρ. It should be particularly emphasized that these properties are absent in the case of ion-cyclotron waves (Guglielmi et al., 1996b).

Reduction of the gravitational acceleration under the action of ponderomotive forces leads to interesting consequences. Let us assume first that all ions are identical in mass. Then $m_+ = m_i$, and Equation (48) may be rewritten as

$$\left(c_s^2 + \frac{\alpha}{\sqrt{\rho}} \right) \partial \rho / \partial s = g \rho \; , \tag{50}$$

where $c_s = (2T/m_i)^{1/2}$, $\alpha = b_0^2 / \mu_0 \sqrt{\rho}$; b_0 and ρ_0 are the values at a specific point on the given field line of the geomagnetic field.

At high latitudes the magnetic field lines are almost radial and therefore Equation (50) can be replaced by

$$\frac{1}{\rho} \left(c_s^2 + \frac{\alpha}{\sqrt{\rho}} \right) \frac{\mathrm{d}\rho}{\mathrm{d}r} = -\frac{\kappa M_\oplus}{r^2} \; . \tag{51}$$

After integrating we obtain

$$\frac{r_0}{r} = 1 + \beta \left\{ \ln \left(\frac{\rho(r)}{\rho_0} \right) + \gamma \left[1 - \left(\frac{\rho_0}{\rho(r)} \right)^{1/2} \right] \right\} \; . \tag{52}$$

Here r is geocentric distance, $\beta = c_s^2 r_0 / \kappa M_\oplus$, $\gamma = b_0^2 / 8\mu_0 N_0 T$, $\rho_0 = \rho(r_0)$, $b_0 = b(r_0)$, $M_\oplus$ is the Earth's mass, κ is the gravitational constant.

The efficiency of the ponderomotive redistribution of plasma is characterized by the value of the dimensionless parameter γ. When passing from $\gamma \ll 1$ to $\gamma \gg 1$ the exponential density profile $\rho(r)$ is substituted by the power one at the distance $r \sim r_0$. If $\beta \ll 1$ then a strong modification of plasma takes place, say, at the distance $r \sim 2r_0$ even at

$$\gamma > \exp\left(-\frac{1}{2\beta}\right) . \tag{53}$$

We now turn to the analysis of multicomponent plasma on the basis of the system of quasilinear Equations (48). The following statement is evident in the case of a single-component plasma, but it needs to be proved in the general case. We argue that the acceleration G is not equal to zero anywhere, and it is pointing downward everywhere. As a consequence the ponderomotive acceleration a is pointing upwards, i.e., we are dealing here with 'electromagnetic lift' of the background plasma. However, $|a|$ is always less than the gravitation acceleration.

Assuming that $G = 0$ somewhere, it follows from Equation (43) that $\partial\rho/\partial s = 0$, and therefore $a = 0$ (see Equation (49)). This means that $G = g$ which is in conflict with the initial assumption. Since $|a| < g$ at sufficiently small distances with certainty, and G is continuous and $G \neq 0$ at any point, then our arguments are true. In particular, this leads to the conclusion that the plasma density decreases monotonically with distance from the Earth, even in the case of the Alfvén wave of high amplitude.

The last conclusion calls for two remarks. First, the possible interference structure of Alfvén waves is disregarded here. Therefore we do not consider a non-monotonic behavior of plasma density in the antinode of standing Alfvén waves (Allan, 1992). Secondly, to avoid confusion, it should be particularly emphasized that our conclusion regarding the monotonic nature refers equally to ion-cyclotron waves, but in low-frequency limit only (see below).

It follows that the dependence of acceleration G on concentrations N_i of ion species $i = 1, 2, \ldots$ is rather complicated to calculate, although we know that the sign of G coincides with that of g. Qualitatively, the ion species are distributed along the geomagnetic field lines in the same way as in the absence of ponderomotive forces. In particular, in a mixture of light ($i = 1$) and heavy ($i = 2$) ions N_2 decreases monotonically with distance but N_1 has a maximum at the same distance.

The value $\gamma + 1$ indicates how many times the local scale height at the point ro increases under the action of ponderomotive forces on the plasma with one sort of ions. In the case of a binary mixture of ions, let us choose r_0 to coincide with a maximum of light ions. Then it follows from Equations (48) and (49) that the local scale height at this point increases by a factor of $\gamma' + 1$, with

$$\frac{\gamma'}{\gamma} = \frac{2m_2}{m_1}\left(\frac{m_2 - 2m_1}{m_2 - m_1}\right)^2 . \tag{54}$$

For example, in the mixture of O^+ and H^+ ions γ'/γ equals 28. This means that the effect of ponderomotive forces increases in multicomponent plasma.

Recall that the Alfvén and ion-cyclotron waves both have been assigned to the common branch of the dispersion curve; the former corresponding to the quasi-transverse and the latter to the quasi-longitudinal propagation. Therefore, it is not surprising, that the Alfvén wave may be modified to the ion-cyclotron one and *vice* *versa* as the wave propagates in the magnetosphere. Thus it is essential to write the equations for the ion-cyclotron waves in a similar form, as above, to the Alfvén waves.

In the case of ion-cyclotron waves we have

$$T\partial \ln N_i/\partial s = \left(m_i - \frac{m_+}{2}\right) g + F_i \ , \tag{55}$$

rather than Equation (48), where

$$F_i = f_i + F \ , \tag{56}$$

$$F = \tfrac{1}{2}(f_e - \textstyle\sum \eta_i f_i) \ . \tag{57}$$

Here $\eta_i = N_i/N$ is the relative concentration of ions, $i = 1, 2, \ldots$, f_e and f_i are defined by equation

$$f = \frac{e^2}{2m\omega(\Omega - \omega)} \left[\frac{\partial E_\perp^2}{\partial s} - \left(\frac{\Omega}{\Omega - \omega}\right) E_\perp^2 \frac{\partial \ln B}{\partial s}\right] \tag{58}$$

with corresponding values of charge and mass. Here $E = b/n$ is the amplitude of electric oscillations, n is the index of refraction.

We want to describe the spatial structure of the wave field. This is a challenging task since the distribution of ions in turn is conditioned by the wave structure. It is convenient to use the WKB relation $E_\perp \propto (B/n)^{1/2}$. It seems likely that there is no other simple way to solve the problem of ponderomotive redistribution of ions without numerical integration of the nonlinear wave equation (Guglielmi, 1992).

In the case of plasma containing only one sort of ions, the set of basic equations reduces to

$$\left[\rho^{1/2} + \frac{c^2 E_{\perp 0}^2 \sqrt{\rho_0}}{4c_s^2 B_0^2 (1 - X)^{1/2} (1 - X\Omega_0/\Omega)^{1/2}}\right] \nabla_{\|}\rho = \left(\frac{g_{\|}}{c_s^2}\right) \rho^{3/2} -$$
$$- \frac{c^2 E_{\perp 0}^2 \sqrt{\rho_0} (\Omega_0/\Omega) X}{4c_s^2 B_0^2 (1 - X)^{1/2} (1 - X\Omega_0/\Omega)^{3/2}} \left(\frac{\rho}{B}\right) \nabla_{\|} B \ , \tag{59}$$

where $X = \omega/\Omega_0$, Ω_0 is the gyrofrequency of ions at a certain point on the given field line. This equation shows a new property of the plasma distribution which was absent in the case of Alfvén waves. Namely, it follows from Equation (59) that the non-monotonic distribution occurs if the pulsations are strong enough. In such a case the maxima of plasma density are located at the minima of magnetic field intensity. In a particular case of the dipole approximation of the geomagnetic field the maximum of ρ is located at the equator if the following condition is fulfilled (Guglielmi et al., 1996b):

$$E_{\perp 0} > E_* = \frac{2\sqrt{2}}{3}\frac{B_0}{c}\left(\frac{R_E g_E}{L}\right)^{1/2}\left[\left(\frac{\Omega_0}{\omega}\right)^{1/2} - \left(\frac{\omega}{\Omega_0}\right)^{1/2}\right] . \tag{60}$$

Here $g_E = 978\,\mathrm{cm\,s^{-2}}$. The critical field $E_*[mV/m] = 231.46[(1-X)\sqrt{X}]L^{-3.5}$ is the smaller, the greater are the McIllwain parameter L and the normalized frequency X (see Guglielmi et al., 1996b).

The measurement of the wave frequency $f = \omega/2\pi$ and amplitude E_0 at the top of a geomagnetic field line would suffice to make an estimate of the dimensionless parameter $\epsilon = E_{\perp 0}/E_*$ which is a convenient characteristic of the efficiency of ponderomotive forces. Instead of $E_{\perp 0}$, the amplitude $b_0 = nE_{\perp 0}$ of magnetic field oscillations may be used and $\epsilon = b_0/b_*$, where

$$b_*(nT) = 0.342\left[\frac{N_0}{L}\left(\frac{\Omega_0}{\omega} - 1\right)\right]^{1/2} . \tag{61}$$

In such a case, not only f and b_0, but also N_0 have to be measured.

Figure 22 (from Guglielmi et al., 1996b) illustrates some partial solutions of Equation 59). Here $Y = \rho/\rho_0$, $Z = \cos\theta$, θ is the colatitude. The boundary condition $Y = 1$ at $Z = 0$ follows from the definition of Y. A solution is controlled by three dimensionless parameters $\epsilon = E_{\perp 0}/E_*$, $X = \omega/\Omega_0$, and $\sigma = c_g/c_s$, where $c_g = (2R_E g_E/L)^{1/2}$. We can see the qualitative redistribution of plasma when $E_{\perp 0}$ increases beyond the critical value ($E = 0.58$ mV m^{-1} at $L = 5$, $X = 0.5$).

The simple theory outlined above applies to the equilibrium distribution of plasma along geomagnetic field lines. It hardly needs to be said that in actual conditions the equilibrium can never be attained. Nevertheless, the general ideas as well as the special results of the theory may be used as a means to analyze satellite and ground-based measurements. Guglielmi et al. (1996b) showed the following illustrative examples.

Bossen et al. (1976) measured Pc1 magnetic pulsations by the geosynchronous ATS-1 satellite. Figure 1 of their work shows a transverse wave with $f \simeq 0.25$ Hz and $b_0 \simeq 3.5$ nT. In a dipole magnetic field, $\Omega_0 = 10.43$ s^{-1} at $L = 6.6$, and therefore $X \simeq 0.15$. Cold background plasma density is needed in addition to these parameters. Lacking precise information we use the characteristic value $N_0 \simeq$ 10–30 cm^{-3}. Then $b_* \simeq$ 1–1.7 nT and $\epsilon \simeq$ 2–3.5, i.e., there is a severe redistribution of plasma under the action of ponderomotive forces.

Fraser et al. (1992) observed the ion cyclotron waves at $f \simeq 0.1$ Hz by ISEE 1 and 2 satellites on the inbound pass near the equatorial dusk on August 22, 1978. On an average, $E_0 \simeq 0.5$ mV m^{-1}, $b_0 \simeq 0.65$ nT, $N_0 \simeq 10$ cm^{-3} at $L \simeq 7.5$ according to Table 1 and Figure 11 of their paper. It follows that $X \simeq 0.1$, $E_* \simeq 0.57$ mV m^{-1} and, hence, $\epsilon \simeq 0.87$. The value of the critical magnetic field $b_* \simeq 1.2$ nT leads us to a somewhat different estimation: $\epsilon \simeq 0.55$. In any case the ponderomotive redistribution of plasma may be pronounced if not as large as in the preceding example.

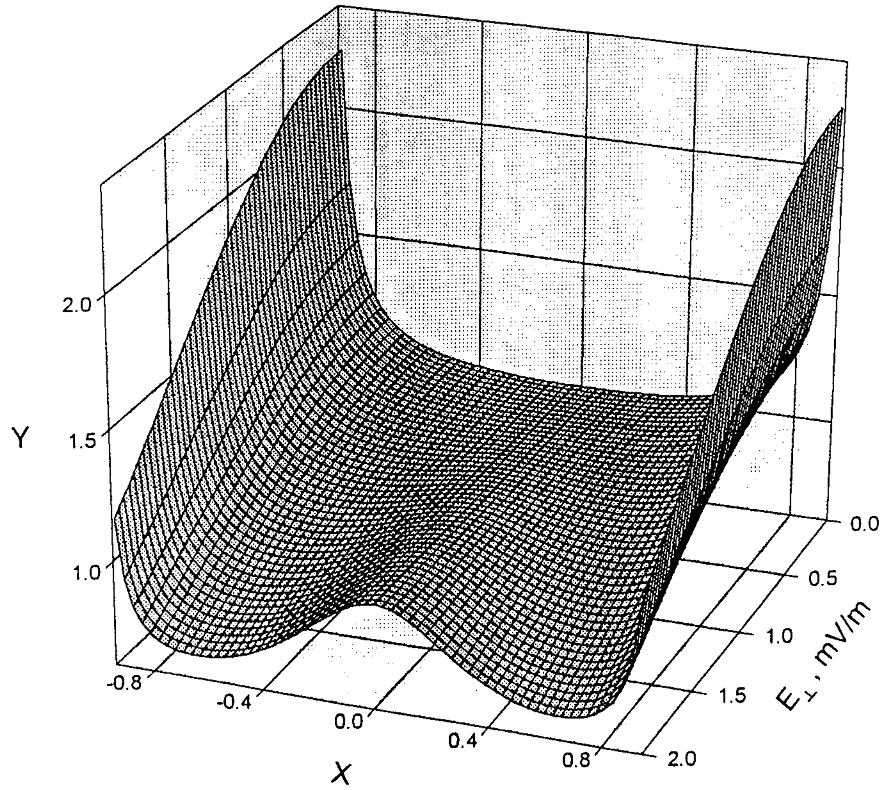

Figure 22. Distribution of normalized plasma density $Y = \rho/\rho_0$ as a function of $X = \cos\theta$ and wave amplitude $E_\perp$. $\theta =$ co-latitude. The figure shows that the plasma re-distribution occurs when $E_\perp > 0.58$ mV m^{-1} at $L = 5$ and $\omega = \frac{1}{2}\Omega_0$, for details, see Guglielmi et al., 1996b.

Mursula et al. (1994c) used the electric field measurements by the Freja satellite to study Pc1 pulsations at ionospheric heights. The wave packet with $f \simeq 1$ Hz, $E \simeq 4$ mV m^{-1} was registered near 645 km altitude at 62° geomagnetic latitude on November 18, 1992. Using the dipole approximation of the geomagnetic field we obtain $L \simeq 5$, so $X \simeq 0.26$ and $E_* \simeq 1.2$ mV m^{-1}. To estimate $E_{\perp 0}$ we use the relation $E \propto (B/n)^{1/2}$ in the form $E_{\perp 0} \simeq E_\perp(B_0/B)[(1 - X)(\rho/\rho_0)]^{1/4}$. The B-ratio and the X-factor attain the values 6×10^{-3} and 0.9, respectively. Let us assume $N \simeq 10^5$ cm^{-3}, $m_i = m_{\mathrm{O}^+}$ and $N_0 \simeq$ 10–100 cm^{-3}, $m_i = m_{\mathrm{H}^+}$. Then $(\rho/\rho_0)^{1/4} \simeq$ 10–20. This gives $E_{\perp 0} \simeq$ 0.2–0.4 mV m^{-1}, and therefore $\epsilon \simeq$ 0.16–0.33.

The dimensionless parameters γ and γ' introduced above are also useful when analyzing satellite observations. As an example, take $E_\perp \simeq 10^2$ mV m^{-1} for an Alfvén wave at an altitude of 10^4 km in the auroral zone. This corresponds to the *Viking* satellite measurements (Lundin and Hultqvist, 1989).

Parameter γ can be rearranged to give

$$\gamma = (m_i/8T)(E_\perp/B)^2 \, . \tag{62}$$

Let us assume that $T \simeq 10^4$ K and m_i is the proton mass. Then $\gamma \simeq 1.7$, i.e., a strong plasma density change is expected.

Therefore, there are good reasons to think that geoelectromagnetic waves in the Pc1-2 frequency range (0.1–5 Hz) may have a pronounced ponderomotive effect on the plasma distribution in the magnetosphere. Among these are the theoretical considerations (e.g., Lundin and Hultqvist, 1989; Guglielmi, 1992; Guglielmi et al., 1996b), and the satellite measurements (e.g., Hultqvist et al., 1988; Gustafsson et al., 1990; Lundin, 1988; Kondo et al., 1990). To this we can add further evidence deduced from ground-based observations of Pc1 magnetic pulsations. For example, we speculate that the activation of so-called pearl pulsations after the magnetic storm (Wentworth, 1964) hastens the refilling of the outer plasmasphere. A possible relation of substorm-associated magnetic pulsations with a rise in O^+ density in the magnetosphere with increasing geomagnetic activity (Young et al., 1982) is a further example of this kind (see also Ashour-Abdalla et al., 1981; Lockwood and Titheridge, 1981; Cahill et al., 1982; Fraser and McPherron, 1982; Kalisher et al., 1982; Perraut et al., 1984; Krimigis et al., 1986; Olsen and Chappell, 1986; Ishida et al., 1987; Kem et al., 1987; Pikkarainen, 1987; Maltseva et al., 1988; Fraser et al., 1992) .

We have considered the ponderomotive redistribution of ions along the geomagnetic field lines, using a simple diffusion equilibrium model. Such an equilibrium does not exist, not at least at high latitudes. Plasma outflow persists at high latitudes as shown by theoretical calculations (Banks and Holzer, 1968; Lundin and Hultqvist, 1989) as well as by satellite measurements (Hultqvist et al. 1988; Lundin, 1988; Kondo et al., 1990). At low latitudes a quasi-equilibrium seems possible. The theory predicts the formation of a maximum of plasma density at the minimum of geomagnetic field if an intense Pc1-2 wave action persists long enough. Although more complete theoretical analysis and experimental verification of the theory is needed, we hope that the theory reviewed above opens new views for a better understanding of the problem. Besides, the theory gives us a convenient way to make rough estimates of the ponderomotive efficiency of Alfvén and ion-cyclotron waves under concrete magnetospheric conditions by using simple parameters like γ, γ', ϵ, and relations like (53), (54), (60)–(62). We conclude from our estimations that the ponderomotive redistribution of plasma in the magnetosphere under the action of Pc1 waves is considerable.

6.3. Short-period pulsations and physics of nonlinear wave motion

Observations of hydrodynamic phenomena have stimulated the emergence of the theory of nonlinear waves. This theory is being advanced by inherent impetus as well as by the demands for simulations in optics, acoustics, radiophysics, meteorology, etc. Geoelectromagnetism in general and physics of short-period pulsations in particular are also important fields of interest for the applications of the theory of nonlinear waves. It is pertinent to recall in this connection that Thomas Gold predicted, on several geomagnetic grounds, the existence of collisionless shock waves.

The wave is nonlinear if its characteristics, i.e., frequency, velocity, waveform, evolution, etc., depend on the amplitude. The measure of nonlinearity may be, e.g., the dimensionless value b/B in the case of Alfvén wave or v/c_{A}, or ξ/λ. Here v is the velocity of medium in the wave field, ξ is the displacement of magnetic field line, λ is the wavelength. The value b^2/p, where p is the pressure of background plasma, offers a useful measure of nonlinearity for the studies of ponderomotive effects. The parameters γ, γ', and ϵ, which have been introduced in the previous subsection, may be used as well.

There are good reasons to think that almost all types of the known nonlinear effects are inherent, to a certain extent, in short-period pulsations. By observing pulsations, we would like to see the generation of the combination frequencies, self-modulation and self-focusing, frequency locking, bifurcation and stochastic attractor appearance, etc. Here we restrict the discussion to the case of self-modulation. We examine a nonlinear effect of the wave propagation in an active magnetoplasma (Guglielmi, 1980; Guglielmi and Repin, 1981).

Let the z axis to be along the direction of the homogeneous external magnetic field. We focus on a one-dimensional case where the wave field depends only on z and t:

$$b_x(z,t) = b_\perp(z,t)\,\exp[ik(z - c_{\mathrm{A}}t)]\ ,$$

$$b_y(z,t) = \mp i b_\perp(z,t)\,\exp[ik(z - c_{\mathrm{A}}t)]\ . \tag{63}$$

Here we suppose that the wave number k is much less than Ω/c_{A}, and the wave amplitude $b_\perp(z,t)$ varies in time and space more slowly and smoothly than $\exp[ik(z-c_{\mathrm{A}}t)]$. The upper (lower) sign corresponds to the left (right) polarization.

The medium is described by two 'conservative' parameters Ω/c_{A}, and two 'dissipative' parameters δ, γ. Here δ is an effective parameter which accounts for all kinds of losses. Let us suppose that the active filling (in the form of a small mixture of resonant particles) leads to instability with the growth rate which has a maximum γ at the wave number k. Then, near the threshold ($|\gamma - \delta| \ll \gamma$) we have the equation

$$\frac{\partial\psi}{\partial t} \pm i\frac{c_{\mathrm{A}}^2}{2\Omega}\frac{\partial^2\psi}{\partial\zeta^2} + i\frac{c_{\mathrm{A}}k}{4}|\psi^2|\psi = (\gamma - \delta)\psi + \frac{2\gamma}{k^2}\frac{\partial^2\psi}{\partial\zeta^2} \tag{64}$$

describing the nonlinear modulation of the low-frequency cyclotron waves in an active medium. Here $\psi = b_\perp/B$, $\zeta = z - c_{\mathrm{A}}t$.

For ion-cyclotron waves (upper signs in Equations (63) and (64)) there exists the soliton solution of Equation (64). It is important that, in contrast to the case of a passive medium, the ion-cyclotron soliton characteristics in an active medium do not depend on initial conditions at all. They are determined completely by the characteristics of the medium. The wave number and carrier frequency are determined by the cyclotron resonance condition (11). The amplitude $b_\perp$ and the width of the soliton Δt are connected by the relation

$$b_\perp \Delta t = \frac{2mc}{e\sqrt{X}} \,, \tag{65}$$

but each of the values $b_\perp$ and Δt is determined separately by the width $\Delta\omega$ of the instability band:

$$b_\perp = \frac{mc}{e}\left(\frac{3}{X}\right)^{1/2} \Delta\omega \,, \qquad \Delta t = \frac{2}{\sqrt{3}\Delta\omega} \,.$$

Here $\Delta\omega = [2(\gamma - \delta)/\gamma]^{1/2} c_{\mathrm{A}} k$, $X = \omega/\Omega$; e, m, and Ω are the charge, mass, and gyrofrequency of ion, respectively.

The relation (65) may be used to test the applicability of theory to Pc1 magnetic pulsations. According to satellite observations, the values $b_\perp \approx 1$ nT, $X \approx 0.2$, and $\Delta t \approx 50$ s are typical in the region of Pc1 generation. These values are in good agreement with the relation (65). Another way to check the theory is to analyze the relationship between the amplitude and the width of wave packets within a given series of Pc1 when the parameter X is likely to be constant. In this case a large volume of ground-based observations is available.

7. Conclusion

More than sixty years have elapsed since the discovery by Harang and Sucksdorff of the short-period geomagnetic pulsations. During these sixty years, the scientists have studied many features of this fascinating natural phenomenon. The lively interest in research of pulsation mechanisms is not decreasing. Maybe this is because of the beauty and complexity of these pulsations. Studies of short-period pulsations are continuing to use both ground- and space-based detectors where the challenge is to measure the wave activity and to interpret it in terms of the physical interactions occurring within the solar-terrestrial environment.

We have shown in this review that many basic principles of interpretation of short-period pulsations have been established. However, many important and interesting problems are still unsolved. Among them the following may be listed:

(1) The physical mechanism of stimulation and suppression of Pc1 prior to SC.

(2) The problem of excitation of Ipdp immediately after SC.

(3) The quantitative study of the relation between the electric field of magnetospheric convection and the frequency rise of Ipdp.

(4) The comparative analysis of Pc1 and Ipdp with the aim to understand the distinction between these two types of pulsations.

(5) Generation of structured Pc1 pulsations and experimental verification of the bouncing wave packet model.

(6) The relation between Pc2, abundance of O^+ in the magnetosphere, and interplanetary magnetic field.

(7) The mechanism of frequency modulation in the morning Ipdp.

(8) Interpretation of the solar-cycle variation in short-period pulsation activity.

(9) The search for the nonlinear manifestation in the properties of short-period pulsations.

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